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Appendix: B
Sea Level Rise

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THE POTENTIAL EFFECTS OF GLOBAL CLIMATE CHANGE ON THE UNITED STATES:

APPENDIX B - SEA LEVEL RISE

Editors: Joel B. Smith and Dennis A. Tirpak

OFFICE OF POLICY, PLANNING AND EVALUATION
U.S. ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, DC 20460

MAY 1989

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PREFACE

The ecological and economic implications of the greenhouse effect have been the subject of discussion within the scientific community for the past three decades. In recent years, members of Congress have held hearings on the greenhouse effect and have begun to examine its implications for public policy. This interest was accentuated during a series of hearings held in June 1986 by the Subcommittee on Pollution of the Senate Environment and Public Works Committee. Following the hearings, committee members sent a formal request to the EPA Administrator, asking the Agency to undertake two studies on climate change due to the greenhouse effect.

> One of the studies we are requesting should examine the potential health and environmental effects of climate change. This study should include, but not be limited to, the potential impacts on agriculture, forests, wetlands, human health, rivers, lakes, and estuaries, as well as other ecosystems and societal impacts. This study should be designed to include original analyses, to identify and fill in where important research gaps exist, and to solicit the opinions of knowledgeable people throughout the country through a process of public hearings and meetings.

To meet this request, EPA produced the report entitled *The Potential Effects of Global Climate Change on the United States*. For that report, EPA commissioned fifty-five studies by academic and government scientists on the potential effects of global climate change. Each study was reviewed by at least two peer reviewers. The Effects Report summarizes the results of all of those studies. The complete results of each study are contained in Appendices A through J.

Appendix	**Subject**
A	Water Resources
B	Sea Level Rise
C	Agriculture
D	Forests
E	Aquatic Resources
F	Air Quality
G	Health
H	Infrastructure
I	Variability
J	Policy

GOAL

The goal of the Effects Report was to try to give a sense of the possible direction of changes from a global warming as well as a sense of the magnitude. Specifically, we examined the following issues:

- o sensitivities of systems to changes in climate (since we cannot predict regional climate change, we can only identify sensitivities to changes in climate factors)
- o the range of effects under different warming scenarios
- o regional differences among effects
- o interactions among effects on a regional level

- national effects
- uncertainties
- policy implications
- research needs

The four regions chosen for the studies were California, the Great Lakes, the Southeast, and the Great Plains. Many studies focused on impacts in a single region, while others examined potential impacts on a national scale.

SCENARIOS USED FOR THE EFFECTS REPORT STUDIES

The Effects Report studies used several scenarios to examine the sensitivities of various systems to changes in climate. The scenarios used are plausible sets of circumstances although none of them should be considered to be predictions of regional climate change. The most common scenario used was the doubled CO_2 scenario ($2XCO_2$), which examined the effects of climate under a doubling of atmospheric carbon dioxide concentrations. This doubling is estimated to raise average global temperatures by 1.5 to 4.5°C by the latter half of the 21st century. Transient scenarios, which estimate how climate may change over time in response to a steady increase in greenhouse gases, were also used. In addition, analog scenarios of past warm periods, such as the 1930s, were used.

The scenarios combined average monthly climate change estimates for regional grid boxes from General Circulation Models (GCMs) with 1951-80 climate observations from sites in the respective grid boxes. GCMs are dynamic models that simulate the physical processes of the atmosphere and oceans to estimate global climate under different conditions, such as increasing concentrations of greenhouse gases (e.g., $2XCO_2$).

The scenarios and GCMs used in the studies have certain limitations. The scenarios used for the studies assume that temporal and spatial variability do not change from current conditions. The first of two major limitations related to the GCMs is their low spatial resolution. GCMs use rather large grid boxes where climate is averaged for the whole grid box, while in fact climate may be quite variable within a grid box. The second limitation is the simplified way that GCMs treat physical factors such as clouds, oceans, albedo, and land surface hydrology. Because of these limitations, GCMs often disagree with each other on estimates of regional climate change (as well as the magnitude of global changes) and should not be considered to be predictions.

To obtain a range of scenarios, EPA asked the researchers to use output from the following GCMs:

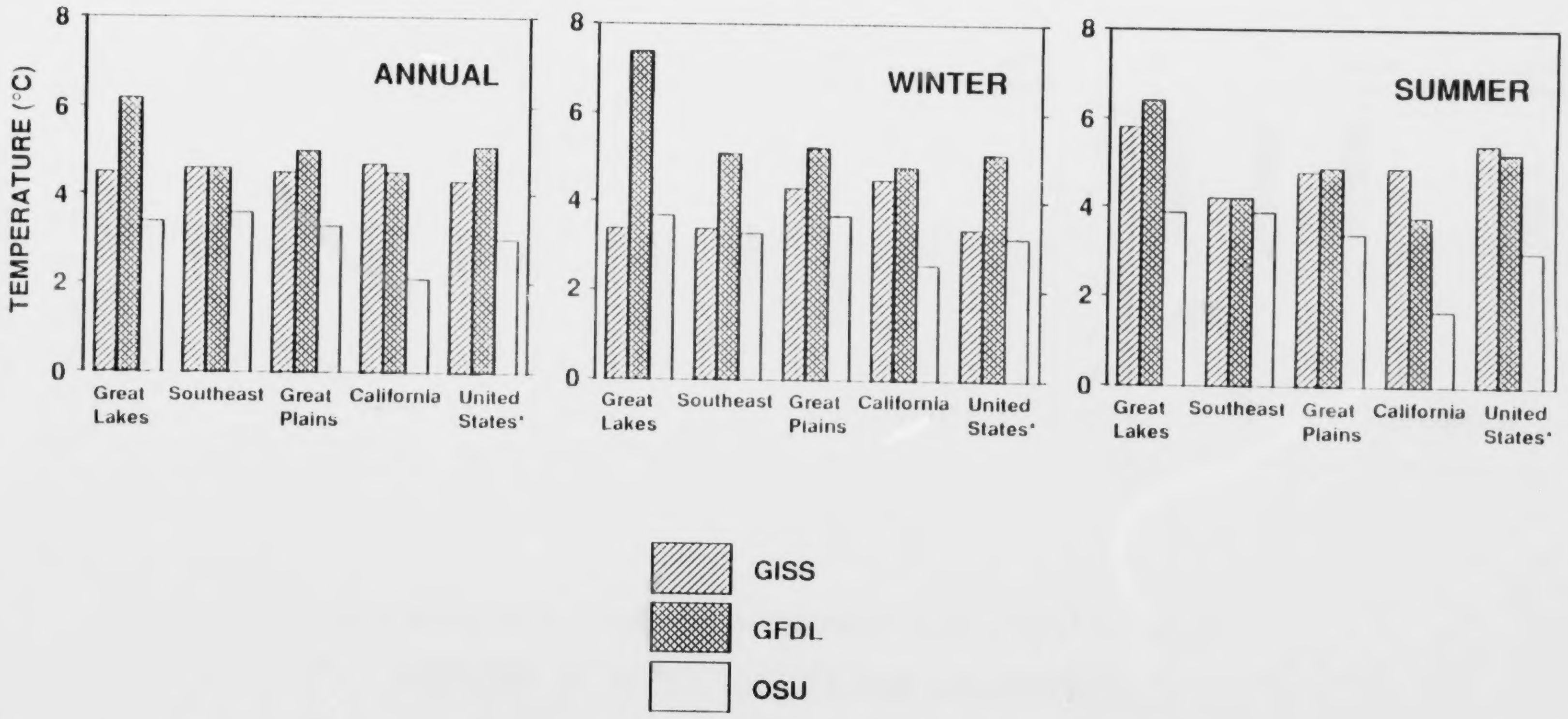
- Goddard Institute for Space Studies (GISS)
- Geophysical Fluid Dynamics Laboratory (GFDL)
- Oregon State University (OSU)

Figure 1 shows the temperature change from current climate to a climate with a doubling of CO_2 levels, as modeled by the three GCMs. The figure includes the GCM estimates for the four regions. Precipitation changes are shown in Figure 2. Note the disagreement in the GCM estimates concerning the direction of change of regional and seasonal precipitation and the agreement concerning increasing temperatures.

Two transient scenarios from the GISS model were also used, and the average decadal temperature changes are shown in Figure 3.

FIGURE 1. TEMPERATURE SCENARIOS

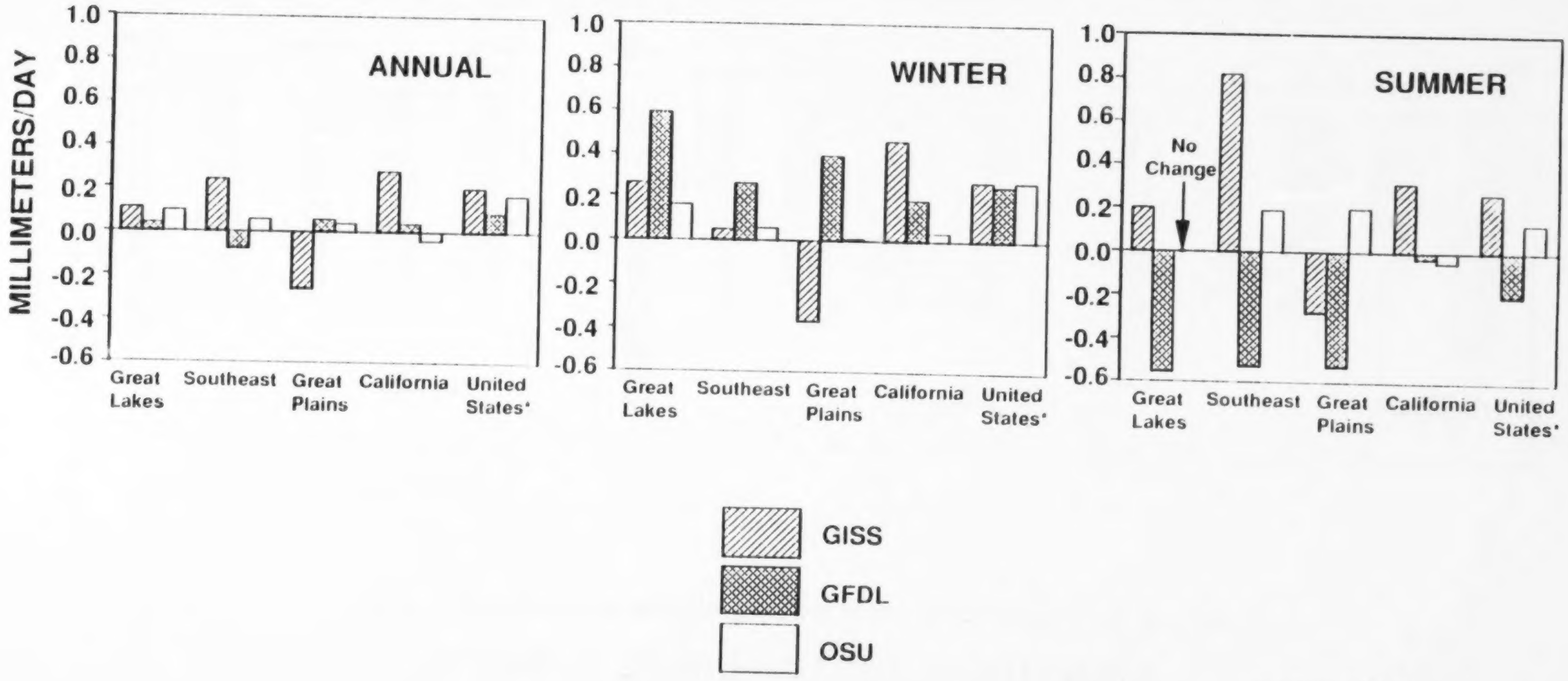
GCM Estimated Change in Temperature from $1xCO_2$ to $2xCO_2$



* Lower 48 States

FIGURE 2. PRECIPITATION SCENARIOS

GCM Estimated Change in Precipitation from 1xCO_2 to 2xCO_2



* Lower 48 States

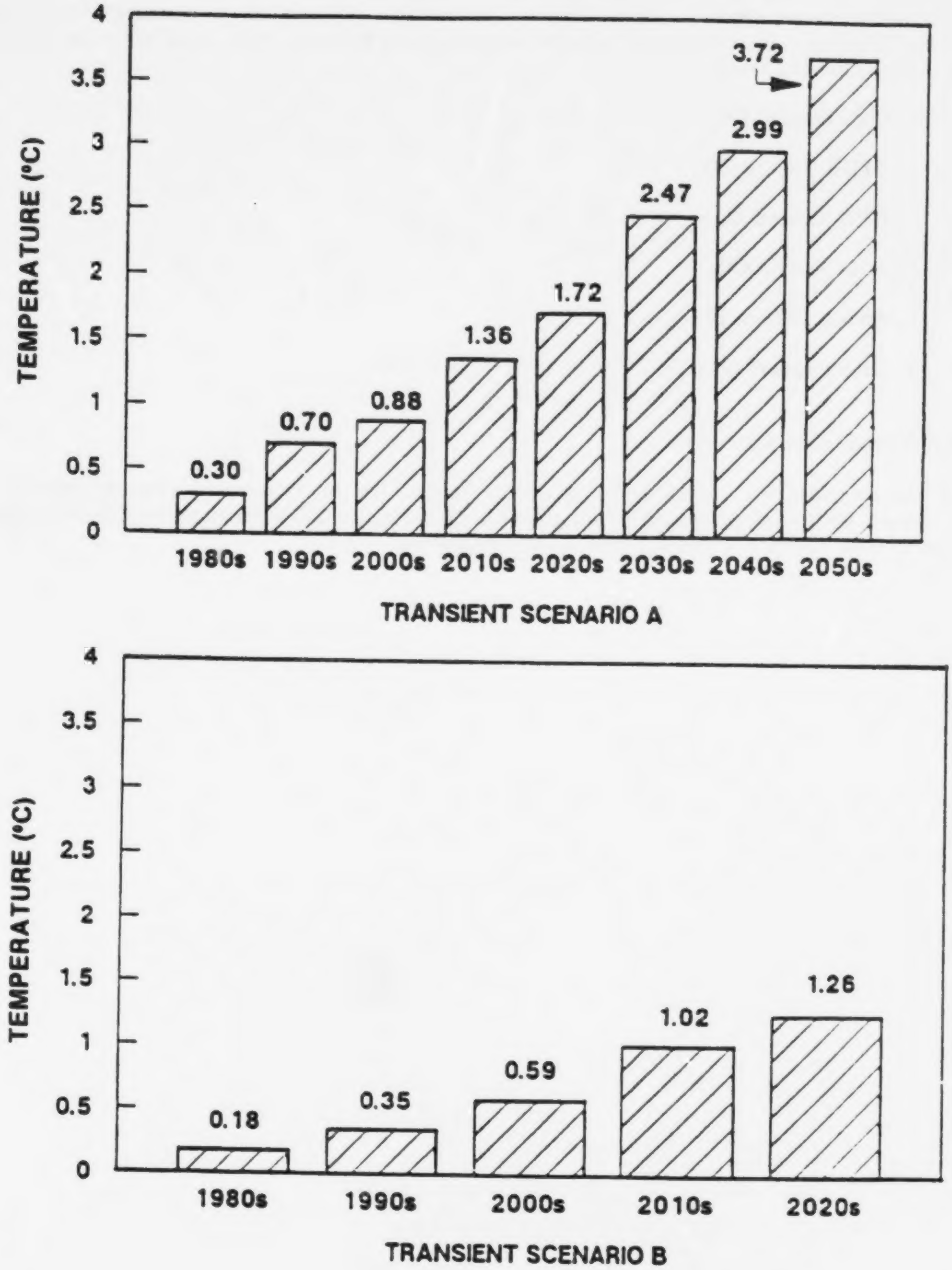


FIGURE 3. GISS TRANSIENTS "A" AND "B" AVERAGE TEMPERATURE CHANGE FOR LOWER 48 STATES GRID POINTS.

EPA specified that researchers were to use three doubled CO_2 scenarios, two transient scenarios, and an analog scenario in their studies. Many researchers, however, did not have sufficient time or resources to use all of the scenarios. EPA asked the researchers to run the scenarios in the following order, going as far through the list as time and resources allowed:

1. GISS doubled CO_2
2. GFDL doubled CO_2
3. GISS transient A
4. OSU doubled CO_2
5. Analog (1930 to 1939)
6. GISS transient B

ABOUT THESE APPENDICES

The studies contained in these appendices appear in the form that the researchers submitted them to EPA. These reports do not necessarily reflect the official position of the U.S. Environmental Protection Agency. Mention of trade names does not constitute an endorsement.

THE EFFECTS OF SEA LEVEL RISE ON U.S. COASTAL WETLANDS

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Cooperative Agreement CR814578-01

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FINDINGS[1]

During the next century, rising sea level due to global warming will have a profound impact on the coastal wetlands of the United States and a significant impact on coastal lowlands. With an almost-certain rise of a half-meter by the year 2100 and with all currently developed areas protected from inundation and erosion, more than 4,000 mi^2 of vegetated wetlands will be lost. With a probable rise of 1 meter by the year 2100, 6,441 mi^2 or approximately 65% of the coastal marshes and swamps of the contiguous United States could be lost. With a 2-meter rise, 7,423 mi^2 or 77% of the coastal wetlands of the contiguous United States could be lost, and remaining southeastern marshes could be converted to mangrove swamps. Furthermore, unprotected barrier islands would be lost through accelerated beach erosion; much of the Florida Everglades and Keys would be inundated; and low-lying coastal cities such as Charleston, South Carolina, and Long Beach, Mississippi, could be submerged if not ringed by dikes. In a worst-case scenario, with a 3-meter rise and all dry land protected from inundation, 10,953 mi^2 of marshes and swamps could be lost.

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[1] Although the information in this report has been funded wholly or partly by the U.S. Environmental Protection Agency under Cooperative Agreement CR814578-01, it does not necessrily reflect the Agency's views, and no official endorsement should be inferred from it.

CHAPTER 1

INTRODUCTION

CONTEXT

The "greenhouse gases" -- carbon dioxide, methane, nitrous oxides, and chlorofluorocarbons that are transparent to sunlight but absorb reradiated heat energy -- are increasing at an alarming rate due to human activities. CO_2 and other greenhouse gases may double by the year 2030 as compared to the amounts present at the start of the industrial revolution (Villach, 1985), warming the earth's surface between 2 and 4°C (Titus and Seidel, 1986). If the average temperature increases by 3°C by 2050 and remains constant thereafter, sea level will probably rise approximately 1 meter (m) by 2100; a global warming of 6°C by 2100 could result in a sea level rise of 2.3 m (Thomas, 1986).

Such an accelerated rise in sea level would have a serious impact on the distribution of U.S. coastal wetlands. Salt, brackish, and fresh marshes as well as mangrove and other swamps would be lost due to inundation and erosion, or would migrate inland as adjacent lowlands not protected by engineering structures are inundated. The value of these wetlands as habitat for wildlife would be impaired, and their biodiversity would decrease. Although many wetlands have kept pace or have increased in area with historic sea level rise due to sediment entrapment and peat formation (Davis, 1985), vertical accretion of wetlands has not been observed to occur at rates comparable to those projected for sea level rise in the next century. In fact, the rate of a 1-m rise by the year 2100 will be equal to that attained during the disintegration of the continental ice sheets at the end of the Pleistocene (Peltier, 1988), which drowned barrier islands and associated features on the continental shelves.

Wetlands are vital to the ecology and economy of U.S. coastal areas. Their biological productivity is equal to that of any other natural or agricultural system (cf. Teal, 1962; Ryszkowski, 1984). Although little of that productivity may be available to marsh animals and coastal fisheries (Montague et al., 1987), over half the species of commercially important fishes in the southeastern United States use salt marshes as nursery grounds (Thurman, 1983). Wetlands also remove pollutants (Pope and Gosselink, 1973) and provide protection from floods, storms, and high tides (Lugo and Brinson, 1978). Based on these functions, it has been estimated that marshes provide an annual return to society equivalent to $5,500/acre (Thurman, 1983). For these and other reasons, the Congress and the U.S. scientific community are seeking the best quantitative estimate of potential impacts on coastal wetlands under various scenarios of sea level rise and coastal zone management policy.

BACKGROUND

Previous studies by EPA indicated the scope of the problems associated with sea level rise (Barth and Titus, 1984; Titus 1986, 1988) and showed that a more detailed study was warranted. As a part of one of these previous studies, Holcomb Research Institute developed a simulation model (SLAMM) that was used to conduct preliminary regional analyses of the effects of sea level rise on U.S. coastal wetlands. The original model was based on manually coded data on elevation and cover classes from topographic maps, using a 1-km^2 grid (Park et al., 1986a,b; Armentano et al., 1988). Simulations suggested that large areas of coastal wetlands would be lost with sea level rise. However, both data and the model needed refining if the results were to be used for evaluating policy. The objective of the present study, therefore, is to present and document the refined databases and calculation procedures, and their limitations, together with improved estimates as to how much of the nation's coastal wetlands are likely to be lost under various scenarios of sea level rise.

CHAPTER 2

METHODS

DATA

Ninety-three sites were chosen, using an unbiased systematic sampling of U.S. Geological Survey topographic maps at a scale of 1:24,000. Starting with the easternmost quadrangle in Maine and restricting the choice to those maps that included some part of the coast, every 15th quadrangle was picked as the center of a site consisting of one to four quadrangles. (Two sites are represented by 1:64,000 maps and two by 1:25,000 maps.) Of these, a subsample of 46 sites was used in this initial study. Four supplemental sites were also chosen for verification purposes. For most coastal sites with low slopes and extensive lowland and wetland areas, a cell size of 500 m by 500 m was used; this is an area of 25 hectares (ha) or 61.75 acres; with this coarse-grained resolution, a site typically contained four quadrangles. For sites with steep slopes or heterogeneous urban development, a fine-grained resolution of 250 m by 250 m (6.25 ha or 15.44 acres) was used; normally such a site was restricted to one quadrangle. A normal coarse-grained site contains as many as 3,400 cells; some sites with fine-grained resolution and covering four quadrangles contain almost 14,000 cells.

Each cell is represented by information on elevation, percent cover in various classes, development, and presence of protective engineering structures. Eleven cover classes were distinguished, including upland (above 12 ft or 3.66 m elevation); lowland (above mean high water spring tide level [MHWS] and below 3.66 m elevation); sandy area (usually backshore and dunes areas, but including both lowland and upland areas characterized by exposed sand); freshwater marshes, saltmarshes, freshwater swamps, mangrove swamps, combined beaches and tidal flats, rocky intertidal areas, and water.

Cover Classes

The cover-class data were obtained by analysis of multispectral Landsat data from essentially cloud-free, geocorrected scenes, augmented by visual interpretation of high-altitude color-infrared photographs (with a scale of 1:58,000). Numerous studies have shown that these forms of remote sensing can effectively differentiate wetland and other coastal cover types (Estes and Thorley, 1983).

Well-established methods for quantifying remotely sensed cover-class data were used (Mausel, 1985). The HINDU algorithm (Dasarthy, 1974) was used to partition the spectral data into classes of repetitive signatures for a particular site. Usually 20 to 30 clusters were obtained. These were combined by an experienced analyst to represent the cover classes on the basis of cluster statistics and spectral signatures, confirmed by information from the maps and photographs. The correspondence between pixels in combined clusters and a designated cover class, such as low marsh, is not perfect. Preliminary analyses of selected sites suggest that accuracies for well-defined classes range from 75 to 95+ percent. Features represented by mixed pixels or by ambiguous spectral responses pose a problem. Residential and commercial developments were not identified from the spectral data because pavement and roofs could be confused with the "sandy area" class. However, because of the need to identify all wetlands, the swamp class was used despite an ambiguous signature. Where possible, high and low marshes were distinguished, based on "dry" and "wet" spectral signatures.

Each Landsat pixel represents an area 57 m by 79 m. The data were resampled and aggregated to form pixels with an area of 71 m by 63 m, and were printed at a scale of 1:24,000 to facilitate comparison with topographic maps. Thus with a 500-m by 500-m grid, the unit cell contains 55+ pixels. The percent cover for each class was stored and reported in increments of 5%.

In the absence of "ground truth" based on detailed field checking, the cover determinations for any particular site should be considered best-estimates consistent with the regional goals of the study. Topographic maps and USFWS National Wetland Inventory (NWI) maps were used to confirm the interpretations. Because the Landsat imagery is often from 1986 and 1987 and supersedes map coverage by a significant number of years, the spectral signatures were often accepted in the event of conflict. For example, at a New Jersey site both the topographic map, photorevised in 1972, and the NWI map, based on 1977 aerial photography, showed an extensive unbroken marsh; however, the Landsat imagery and the high-altitude photograph provided unmistakable evidence that a large area had been converted to lowland (probably with dredge fill). Marshes, shadowed uplands, and uplands with redwoods sometimes exhibited similar spectral signatures; these were reassigned manually on the basis of topographic maps. Swamps proved to be difficult to distinguish from upland forest; a dense tree canopy can effectively mask any standing water. For several sites swamps were reassigned manually, based on topographic maps. Because sandy areas often included beaches and tidal flats, these wetlands are underestimated in the data, and a transient response is often observed in the simulations as the model reapportions sandy area to beach.

Development

Residential and commercial developments were identified from topographic maps. If a cell contained sufficient buildings and other structures worthy of protection (including airports and wharves), the cell was characterized as developed. Because the maps are older than the Landsat data and the simulations start with the Landsat coverage, this underestimates the extent of development and subsequent protection. Although it would be of interest to simulate continued coastal development, that is beyond the scope of this study.

Elevations

Topographic elevations on U.S. Geological Survey maps are relative to the 1929 sea level, known as the National Geodetic Vertical Datum (NGVD); therefore, elevations of the dry-land classes (upland, lowland, and sandy area) were corrected for historic sea level rise from 1929 to the date of the topographic map. The long-term value of 1.2 mm/yr was used for historic sea level rise.

Dry-land elevations were further corrected for changes from the map date to the date of Landsat coverage, at which time the areas of the classes were observed. This correction is based on both the 1.2 mm/yr trend and observed subsidence due to regional isostatic adjustments and tectonics, and local compaction due to withdrawal of water, oil, and gas .

The elevational data were obtained by digitizing the corner elevations of each cell, based on interpolations of elevations from the topographic maps. Both the elevational and the Landsat data were recorded using the Universe Transverse Mercator grid and were combined for each cell in the site data file. Elevations and elevational ranges for classes within a cell were apportioned based on an algorithm that assumes sandy and rocky areas to have a convex profile, and other lowland and upland areas to have a concave profile. An elevational mosaic was assumed for saltwater wetlands, with each cover class traversing its full elevational range within a cell (representing the usual microtopography that occurs with small tidal flats and beaches, tidal creeks, natural levees, and back-levee areas). Saltwater wetland elevational ranges were computed by assuming constant relationships of the wetlands to tidal datums (cf. Lefor et al., 1987), with mean or half tide level (MTL) as 0; beach and tidal flats extending from mean low water (MLW) to mean high water (MHW), or from MLW to MTL on coasts with low wave energy and vegetated wetlands; low marsh extending from MTL to MHW; high marsh extending from MHW to MHWS; and mangrove swamps extending from MTL to MHWS. (Occasionally saltwater wetlands occur above MHWS, but the area is small and can be ignored.)

QUALITY ASSURANCE

Quality assurance, mandated by the EPA Administrative Procedures Act, received close attention in this study. All interpretations and implementations received an independent evaluation by another member of the study team, and records have been kept for all procedures.

Selected sites were visited by the principal investigator and members of the remote sensing team. This helped provide ground truth for representative sites and promoted inclusion of subtle relationships in the model.

Discussions of the modeling study were held at several coastal wetland labs, and suggestions for improving the study were solicited.

DESCRIPTION OF MODEL

Stated simply, the objective of the modeling undertaken in this study has been to consider the dominant processes involved in vegetative wetland conversions and related shoreline reconfigurations during long-term sea-level rise. The model, SLAMM2, differs from other wetland models (Day et al., 1973; Wiegert et al., 1975; Hopkinson and Day, 1977; Browder et al., 1985; Sklar et al., 1985; Costanza et al., 1987; Kana et al., 1988) by its ability to predict map distributions of wetland cover under conditions of accelerated sea level rise and by its applicability to the diverse wetlands of the contiguous coastal United States.

Eleven cover-classes were modeled in each of over 3,000 cells for 115 or more years; therefore, the level of scientific detail represented had to be balanced with efficient computational algorithms. The following sections present the basic constructs for each of the processes considered in order to establish the basis for the model results; the constructs are organized in two sections, the basic inundation model and the map-based spatial model. Simplifying assumptions that may bias the results, and could be investigated more fully in the future, are emphasized by italics.

Inundation Model

The colonization of newly inundated dry land by wetland vegetation and loss of wetlands due to further inundation is based on a straightforward geometric relationship, with lag effects for some conversions. Seven processes are considered as part of the inundation model.

Sea Level Change. Relative sea level (SL) after 1986 was computed for a given year T in the simulation, using a quadratic equation:

$$\mathbf{SL = Linear * (T - 1986) + Quadratic * (T - 1986)^2 + Subsidence}$$

where **Linear** is the historic eustatic trend of 1.2 mm/yr and **Quadratic** is the second-order parameter with values depending on the scenario chosen (Figure 1). **Subsidence** is a site constant for the rate of local subsidence, and is based on the rate observed at the site or at the nearest place of record. Usually subsidence reflects regional isostatic and tectonic responses, is not large, and does not vary greatly over the region; however, subsidence may be large, due to groundwater and petroleum withdrawal and compaction of unconsolidated sediments, and may be both local and time-varying. Although high rates were not extrapolated to other sites, they were assumed to apply to the entire site in which they were observed and to be constant over time. Insofar as pumping may be curtailed, *use of high subsidence values may overestimate inundation effects for a few sites.*

Conversions between Classes. SLAMM2 is a discrete, algebraic model with a time step of 5 to 25 years (depending on the rate of sea level rise) that utilizes alternative pathways of change, depending on site and cell conditions. Conditions include exposure to open ocean, residential and commercial development, existence of protective engineering structures, unconsolidated or consolidated substrate (based on geologic maps), prevailing wave regime, and subtropical climate. Each class occurring in a cell is converted to another class for given conditions. Generally, the conversion is fractional and is represented by the following equation:

$$\mathbf{Loss_{Class} = SLRise/Range_{Class} * Vulnerability * DeltaT}$$

where $\mathbf{Loss_{Class}}$ is the fraction converted in the time step; **SLRise** is the change in sea level during the time step, corrected for sedimentation and vertical accretion of wetland where appropriate; $\mathbf{Range_{Class}}$ is the elevational range of the class in a given cell; **Vulnerability** is the susceptibility to change due to factors such as slow death and colonization (important only for some processes such as inundation of mangrove swamps and only for a time-step of five years); and **DeltaT** is the time step. This construct assumes that conversion of area from one

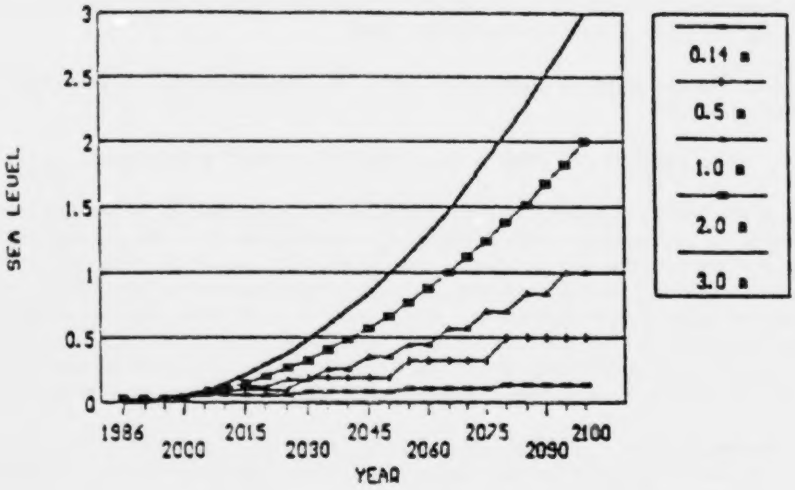


Figure 1. Sea-level rise scenarios used in the study; the step wise patterns indicate the longer time steps used for some scenarios.

class to another is a linear function of the elevational range that is lost due to sea level rise within the cell. Departures from a linear slope are assumed to be accounted for in the biasing of elevational ranges toward higher values for convex slopes and lower values for concave. These are simplifying assumptions; therefore, *conversions may occur at a faster or slower rate than simulated, and the simulations should be considered as approximate responses to be expected for different scenarios and should be used primarily for computing regional averages.*

Tropical Conditions. The conversion of dry land to wetland vegetation is complicated by global climate change. Mangroves are limited to those areas without appreciable frost. At present, viable populations of small black mangroves occur as far north as Daytona, Florida, and in the Mississippi River delta and along the barrier islands of the northern Gulf of Mexico (Sherrod and McMillan, 1985). With only a slight decrease in killing frosts, these populations could spread to other coastal areas where adjacent water moderates the climate. The SLAMM2 simulations assume that for all scenarios other than a continuation of the current sea-level trend, mangrove swamps can become established in the northern Gulf of Mexico and Atlantic coast of Florida beginning in the year 2000. They are assumed to grow in Georgia and South Carolina at slightly later dates. This is an approximation and could be sharpened by using projected climatic changes for each area of the coast.

Coastal Engineering Structures. The presence of dikes and levees completely enclosing coastal areas was noted from the topographic maps. The two protection scenarios represent further construction of dikes around all developed areas and all dry land, respectively. Areas so protected are not allowed to convert to other classes in the simulations. *Enclosed wetlands are assumed to be maintained in their initial condition.*

Death and Colonization. Death and conversion of low marsh to water by inundation and corresponding conversion of high marsh to low marsh are assumed to occur at a linear rate of 20% per year of the potential based on inundation alone (**Vulnerability** = 0.2); with a normal time step of five years or more, this produces no discernible lag. However, in the model, mangrove swamps are converted to water at the rate of 10% per year of the potential, producing a 50% lag for a time step of five years. Because they are intolerant to saltwater, freshwater swamps and marshes are converted instantaneously to water or high marsh, respectively, or to mangrove swamp if subtropical.

Inundated lowlands and sandy areas are instantaneously converted to either high marsh or mangrove swamp by the model. This assumes colonization to proceed faster than the normal five-year time step, and it assumes that paved surfaces are a negligible impediment to colonization. Although relatively rapid colonization rates have been reported for some areas, these assumptions may lead to an overestimate of vegetated wetlands.

Sedimentation and Accretion. One of the pervasive challenges in developing the model was to incorporate processes with variable rates known from studies in different areas but not known for the specific study sites. Perhaps the most important process is vertical accretion of wetlands. In the past in many areas, accretion has kept pace with local changes in sea level. Although accretion rates vary widely at particular locales and among areas, including most of the study sites, a pattern emerges that can be used in estimating local rates. In deltaic areas characterized by extensive marshes, 10 mm/yr seems to be representative, although much higher maximal values have been observed; in many areas with moderately extensive wetlands, 5 mm/yr seems to be a common midrange value; in areas with little wetland development, 2 mm/yr seems to be a representative minimal value (cf. Letzsch and Frey, 1980; Gosselink, 1984; Armentano et al., 1988). Therefore, as a simplifying assumption, if the percentage of salt wetlands at the start of the simulation is greater than or equal to 30%, an accretion rate of 10 mm/yr is used for low marsh at the site; if greater than 5% and less than 30%, an accretion rate of 5 mm/yr is used; if less than or equal to 5%, an accretion rate of 2 mm/yr is used. Because marsh areas that are back from water courses tend to have accretion rates that are approximately half those of streamside marshes (cf. Gosselink, 1984), the values are halved for high marsh. Areas enclosed by dikes are not affected by these accretion rates because the marshes are not permitted to change.

Rates of accretion in mangrove swamps seem to depend more on extremely localized conditions and have not been well studied. In a detailed study of a mangrove swamp in Australia, Bird (1986) reported rates varying from 2 to 13 mm/yr. We have assumed 5 mm/yr to be representative and have used that value for all areas with mangroves.

The assumption of an accretion rate for a particular wetland type that is uniform over a site and constant through time probably leads to an overestimate of wetland maintenance.

Sedimentation rates in adjacent areas of sheltered water have not been well documented, nor are they as important as accretion; therefore, the local sedimentation rate for areas of sheltered water is taken to be one-tenth that of accretion. Admittedly this is an arbitrary value, but the model is not sensitive to it.

Few U.S. beaches are currently prograding or expanding due to sedimentation. The model assumes that progradation of exposed beaches and tidal flats occurs only under conditions of high sedimentation and a continuation of historic sea level rise. If sedimentation exceeds sea level rise under any scenario, areas of sheltered water are converted to tidal flats which in turn are converted to wetlands, using the following relationships:

$$\mathbf{Loss_{Water} = (DeltaT * Sedimentation - SLRise)/Depth}$$

$$\mathbf{Loss_{Tidalflat} = (DeltaT * Sedimentation - SLRise)/Range_{Tidalflat}}$$

where $\mathbf{Loss_{Water}}$ is the fraction of area of water converted to tidal flat during the time step **DeltaT**; **Sedimentation** is the rate of sedimentation (m/yr); **SLRise** is the change in sea level during the time step; **Depth** is the average depth of sheltered water; and $\mathbf{Range_{Tidalflat}}$ is the elevational range of tidal flats at the site. The construct treats the fractional losses as uniform for all cells with sheltered water and tidal flats, and it ignores subsidence; therefore, it probably overestimates progradation at sites with high sedimentation rates (as indicated by extensive initial wetlands) for the scenario of continued historic sea level rise.

Salinity. Salinity is not explicitly modeled. This has two consequences in the simulations: low-lying freshwater marshes may be designated as saltmarshes, and salt pannes and tidal flats in arid regions may be predicted to convert to saltmarshes, on the basis of elevation.

Spatial Model

In addition to the effects of inundation represented by the simple geometric model described above, second-order effects occur due to changes in the spatial relationships among the coastal elements. Accordingly, SLAMM2 incorporates a map-based model component to consider four spatially important processes: coastal beach erosion, overwash, barrier breaching, and headland erosion..

Erosion. Under equilibrium conditions, erosion and deposition balance and wetlands are not lost. However, even historic sea level rise coupled with local subsidence has upset coastal equilibrium in many parts of the world (Bird, 1986; Bruun, 1986). Although the processes of erosion can be expressed by detailed quantitative relationships, such an approach is beyond the scope of the present study. Rather, qualitative relationships are defined and used as thresholds for including constant rates of wave erosion in simulating the localized loss of wetlands. The effects of severe storms are included in these average values. The model can represent several levels of erosion based on the observed average fetch (the distance across which wind-driven waves can be formed) of sheltered water. These levels are represented by scalars: "none," "little," "moderate," "heavy," and "severe"; however, in the present implementation, constant erosion is triggered only when the erosional scalar is greater than "moderate," which occurs when the average fetch exceeds 9 km. This occurs at only a few sites.

The model also recognizes exposure to open ocean as triggering erosion of wetlands. Cells can become exposed as protective barrier islands and spits are breached. If a saltmarsh is exposed to the open ocean or erosion is greater than "moderate," 0.4% of the marsh is lost per year (2 m/yr using a 500-m grid). If a swamp is exposed to the open ocean or erosion is greater than "moderate," 0.2% of the swamp is lost per year (1 m/yr using a 500-m grid). These values are based on the literature (Hall et al., 1986) and on rates observed from photorevised and sequential maps of areas with eroding wetlands.

Bruun (1962, 1986) has shown that on the average, recession of beaches and backshore areas is one hundred times the change in sea level. Assuming a beach slope of 12°, an average for many beaches (cf. Dyer 1986), the width is five times the height (tan 12° = 0.2). Therefore,

$$\mathbf{Recession = 100 * SLRise}$$

$$\mathbf{WidthBeach = 5 * Range_{Beach}}$$

$$\mathbf{Loss_{Beach} = Recession/WidthBeach}$$

where **Recession** is the width of beach lost during a time step (m); **SLRise** is the change in sea level (m) during the time step; **WidthBeach** is the theoretical width of the beach (m); $\mathbf{Range_{Beach}}$ is the elevational range of the beach (MHWS-MLW in m); and $\mathbf{Loss_{Beach}}$ is the fraction of beach lost during a time step.

Assuming that beach width is maintained at the expense of any adjacent backshore and dune area, and assuming that the beach runs the length of the cell (an assumption that probably results in an overestimation of beach area), then

$$\mathbf{AreaBeach = WidthBeach * Scale/10{,}000}$$

$$\mathbf{Recession_{SandyArea} = AreaBeach - Area_{Beach}}$$

while there is a deficit of beach and there is sandy area to be eroded; if the "protect backshore" scenario is chosen, recession is not allowed. **AreaBeach** is the theoretical area of beach (ha), given equilibrium conditions; **Scale** is the grid size, usually either 500 or 250 m; **10,000** is a proportionality constant to convert meters to hectares; $\mathbf{Recession_{SandyArea}}$ is the sandy area converted during the time step (ha); and **AreaBeach** is the area of the beach before conversion of adjacent sandy area (ha).

Beaches that are developed are assumed to be protected; therefore, developed backshores are not allowed to erode in the simulations unless a "no protection" scenario is chosen. However, no provision is made for active formation of natural and artificial dunes on undeveloped beaches, nor is natural nourishment of beaches due to eroding headlands simulated. Therefore, the model probably overestimates beach erosion on exposed, undeveloped coasts.

Overwash. As erosion of backshore and dune areas occurs and as other lowlands are drowned, wetlands on the lee side of coastal barriers are subject to conversion due to overwash, the process by which sediments are carried over the crest of the barrier and deposited onto adjacent wetlands. This process is simulated only for areas having a beach and only during the time step in which the lowland is breached. It assumes that 50% of the adjacent high marsh, 25% of the low marsh, and 5% of mangrove (if present) in the adjacent cell is converted to beach and tidal flat; the percentages are educated guesses based on observations of existing overwash areas (cf. Leatherman and Zaremba, 1986). Adjacent water is converted to beach and tidal flat by an amount based on the assumption that upper beach sediments (occurring between mean tide level and mean high water spring tide level) are transported into the water:

$$\mathbf{Loss_{Water} = (MHWS - MTL)/Depth}$$

where $\mathbf{Loss_{Water}}$ is the fraction converted.

Exposure to Open Ocean. Breaching of coastal barriers results not only in overwash but also in exposure of areas to the open ocean. At the beginning of the simulation, the model changes cells from unexposed to exposed if they are in line, based on prevailing wave direction, with exposed water and without intervening areas other than water. Each time overwash occurs, cells on the lee side are changed to exposed, and with each time step the adjacent cell on the lee side is changed to exposed if that cell is all water. This effectively limits erosion in the once-sheltered water areas and mimics the continuation of shoal-water conditions.

Erosion of Headlands. Erosion of sandy areas is simulated to maintain equilibrium with adjacent beaches; but erosion of lowlands and uplands that do not have a multispectral signature indicating sand is not simulated. Therefore, recession of sandy areas is probably overestimated by the model, but erosion of other dry lands is ignored.

In summary, the model probably errs slightly toward maintenance of wetlands and toward accelerated loss of barrier islands, but overall it provides prudent forecasts useful in guiding policies for coping with sea level change.

CHAPTER 3

SIMULATIONS AND SYNTHESIS OF RESULTS

As would be expected from the major differences in coastal physiography around the United States, the potential for loss of wetland resources due to a rise in sea level varies widely from region to region. Thus, balanced sampling was required for both the regional and national estimates of losses. Each site was chosen using an unbiased sampling procedure (see DATA) and covers an area from the open ocean to uplands (or diked lowlands) so that both loss and migration of wetlands can be evaluated. The standard set of simulations for each site spans a period from the date of the remote imagery to the year 2100 and provides estimates of response to:

- a projection of the historic trend of sea level rise (1.2 mm/yr) (resulting in a eustatic sea level stand of 0.14 m above 1986 level by the year 2100); and 1/2-, 1-, 2-, and 3-meter sea levels by the year 2100
- no protection of dry lands, protection of backshore areas of beaches only, protection of all developed areas, and protection of all dry land (including enclosed wetlands)

The sea level scenarios are based on projections given by Thomas (1986), assuming different global-warming scenarios and the possible melting of glacial ice and thermal expansion of the upper layers of the oceans. The 1-meter scenario is considered most probable in the absence of significant efforts to curb global warming.

The protection scenarios are intended to represent different levels of defending coastal areas from inundation and erosion. With the "no protection" scenario, only those areas already protected by levees and dikes will be protected in the future. The "protect backshore" scenario proved to be uninteresting and was not used in the summaries; it was intended to represent the protection of backshore areas (especially on barrier islands) through sand nourishment and bulkheads, without protection of adjacent lowlands. Protection of developed areas represents the effects of enclosing all existing developed areas (see **DATA**) with dikes and levees; it is conservative in that further development is not considered. The extreme scenario is protection of all dry land; note that this can lead to protection of freshwater wetlands that are landward of dry land.

CASE STUDY: LONG BEACH, NEW JERSEY

One case study is presented here to illustrate the level of resolution sought in the database, in the simulation of changes over time, and in the computational and summarization procedure. Long Beach Island, New Jersey, and the adjacent bay and low-lying mainland comprise a typical barrier island system to the south of Atlantic City (Figure 2). The data analysis and simulations of this site provide both insights into, and limited verification of, the SLAMM2 algorithms.

Examination of the map shows undeveloped and developed dry land, saltmarsh, swamp, and water (Figure 3). An enlarged portion of the map (Figure 3B) shows the 500-m by 500-m cells formed by aggregation of classes from the unsupervised classification of the Landsat multispectral data, represented by the pixel map (Figure 3C). Interpretation of the Landsat data was facilitated by comparison with the high-altitude infrared photograph of the same area (Figure 3D). The elevations and locations of developed areas were obtained from the topographic map (Figure 3E). The National Wetland Inventory map (Figure 3F) was used to confirm the interpretations of the classes.

Detailed examination of the maps demonstrates two problems. Only the dominant class is plotted in the computer-generated map (Figure 3A,B); therefore, some of the islands are not shown because the cells happened to cover more water than marsh. Also, the swamp in the northwestern corner of the site probably includes forested upland.

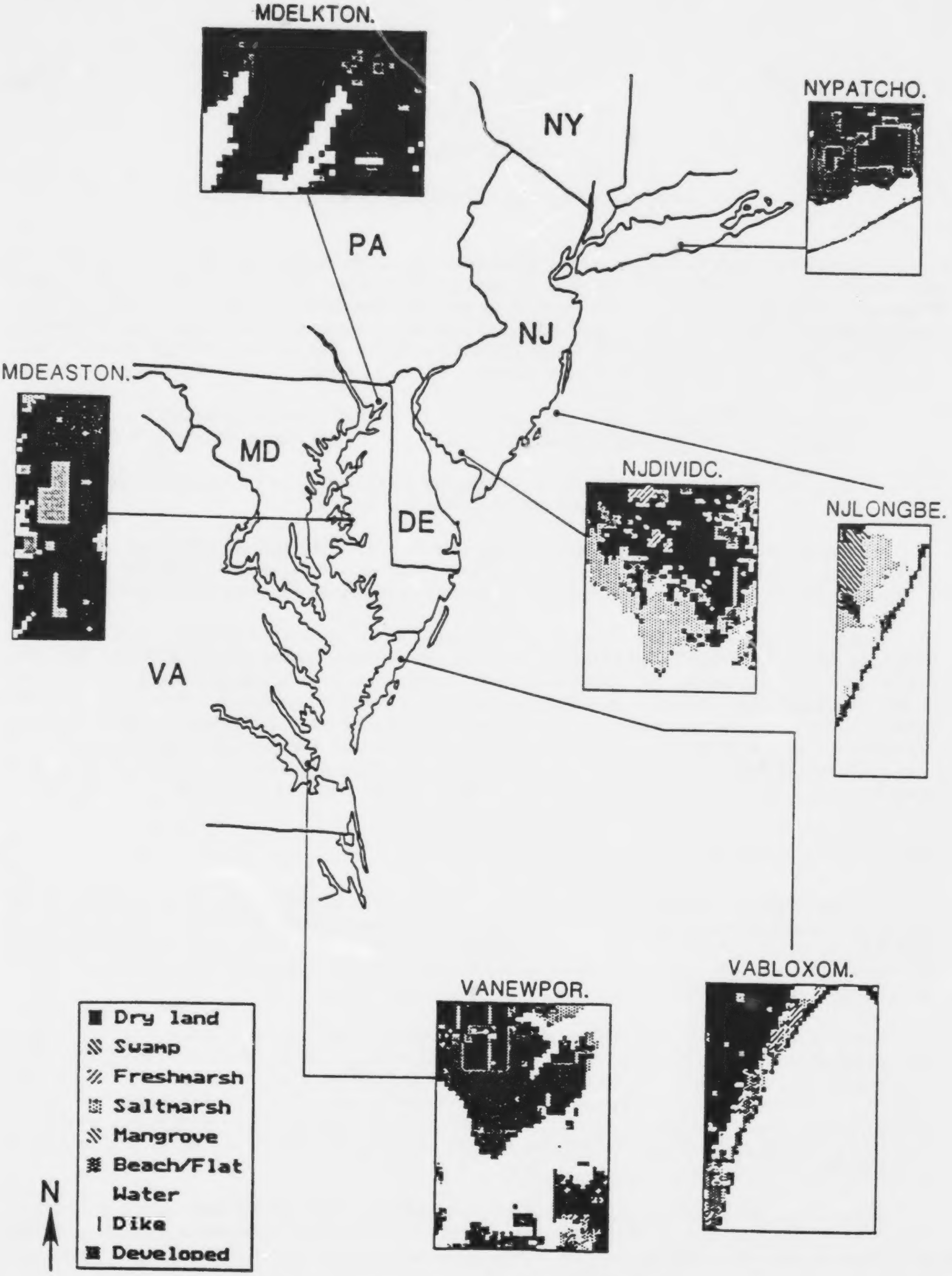

MDELKTON.
NYPATCHO.
NY
PA
NJ
MDEASTON.
MD
DE
NJDIVIDC.
NJLONGBE.
VA
VANEWPOR.
VABLOXOM.
Dry land
Swamp
Freshmarsh
Saltmarsh
Mangrove
Beach/Flat
Water
Dike
Developed
N

Figure 2. Index map of the mid-Atlantic region.

km 0
300
mi 0
300

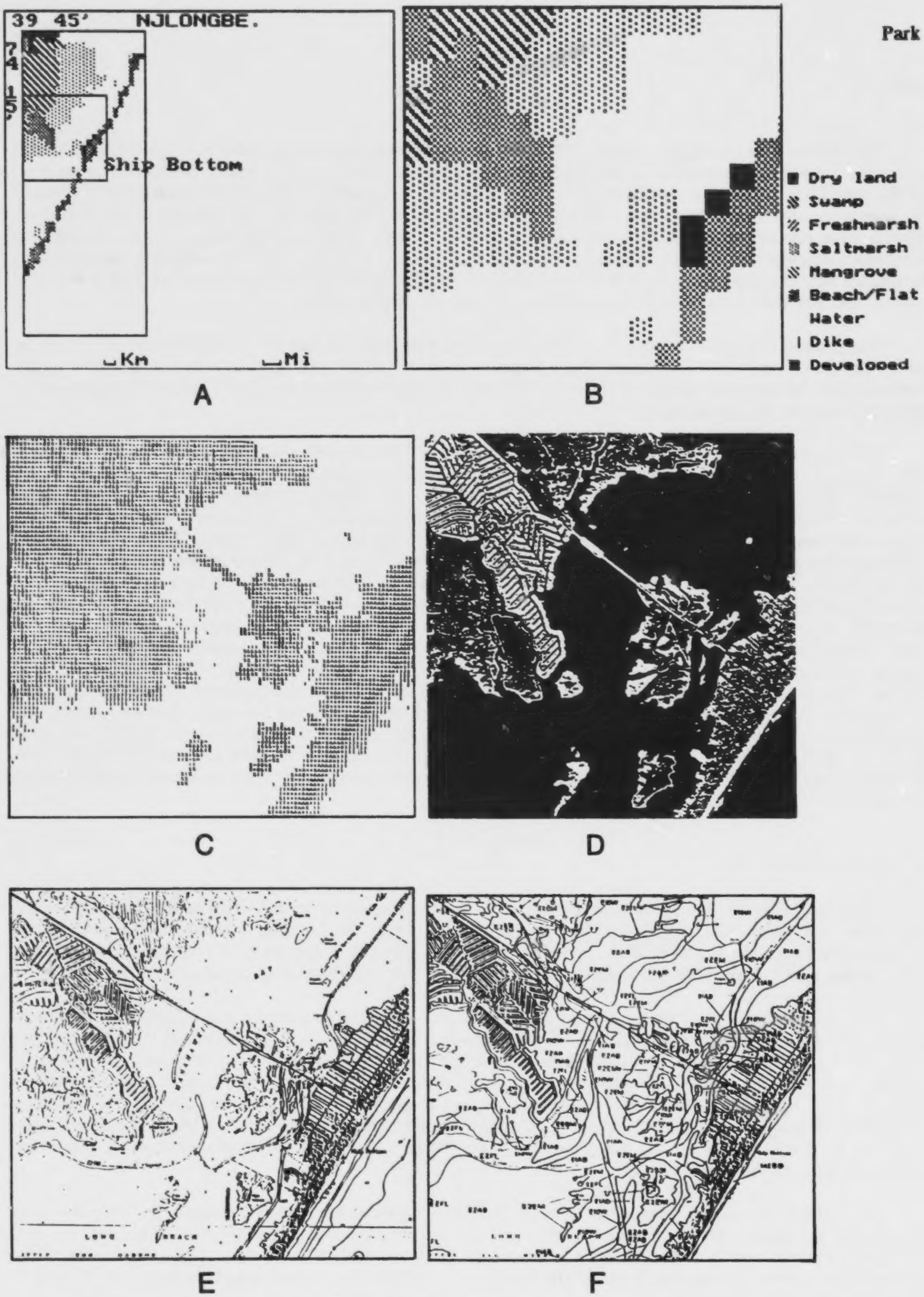

39 45'
NJLONGBE.
Ship Bottom
Km
Mi
Park
Dry land
Swamp
Freshmarsh
Saltmarsh
Mangrove
Beach/Flat
Water
Dike
Developed
A
B
C
D
E
F

Figure 3. Maps of the Long Beach, New Jersey, site showing (A) the initial computer-generated map, (B) an enlargement of part of the map, and corresponding scenes from (C) the Landsat pixel map, (D) the high-altitude infrared photograph, (E) the topographic map, and (F) the National Wetland Inventory map.

The impact of sea level rise perhaps is best visualized by maps representing different scenarios of sea level rise, with and without protection of developed areas (Figure 4). Marsh persists with a 14-cm rise in sea level by the year 2100, although a significant area of swamp is lost by inundation (Figure 4B); more likely, some of the area presently covered by swamp will slowly be converted to saltmarsh, but that transfer is not simulated. With a 0.5-m rise by the year 2100, most marsh is lost (Figure 4C). There is little change with 1-, 2-, and 3-m rises when developed areas are protected (Figure 4D-F); however, without protection, saltmarsh would be free to migrate onto the unpaved areas of developed lowlands such as those west of Ship Bottom (cf. Figure 4G), and with 2- and 3-m rises Long Beach Island would be breached (Figure 4H,I).

The gradual changes in cover and decline of wetlands with sea level rise are portrayed most effectively by an area graph (Figure 5). It is apparent that wetlands will be lost rapidly with any sea level rise greater than the historic trend; furthermore, almost all saltmarsh is lost by the 2080 when an 0.8-m rise is reached, using the most probable scenario of 1 m by the year 2100.

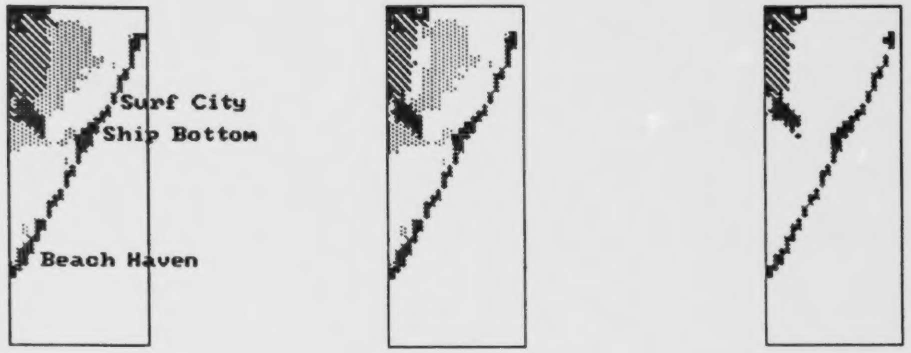
This projection is quite different from that of Kana et al. (1988) based on detailed transects and application of a simple geometric model. They concluded that essentially no wetland would be lost by 2075, given the 1-m scenario. Examination of their composite transect for the area (Figure 6) shows why their results are so different. They used two feet as the tidal range, whereas we used one foot, as reported on the Long Beach topographic map; but, more important, the marsh zones are displaced well above normal levels relative to the tidal range (equivalent to that expected for a 5-foot tidal range). Kana et al. (1985) attribute this to alteration of the hydrology by mosquito ditches; however, it is possible that the same regional hydraulic gradient that promotes the adjacent swamps is responsible for maintaining wetter conditions than would be expected from tidal conditions alone. Compounding the discrepancy in predictions, we interpreted the marsh to be low based on a "wet" spectral signature, whereas Kana et al. (1985) found that high marsh dominated (Figure 6). We were unable to duplicate their projection of no marsh loss by imposing a 5-foot tidal range with high marsh instead of low. They assumed a uniform sedimentation and accretion rate of 5 mm/yr, compared to our assumption of 5 mm/yr for low marsh, 2.5 mm/yr for high marsh, and none for adjacent lowland; however, varying the accretion rate of low marsh from 2 mm/yr to 10 mm/yr only changed the timing of the loss of saltmarsh predicted by SLAMM2 by approximately 17 years (Figure 7). It is difficult to reach any conclusions from this attempted verification, but it is quite possible that our projection of total loss of marsh is more realistic, given the tendency for flooding.

NATIONAL IMPACTS

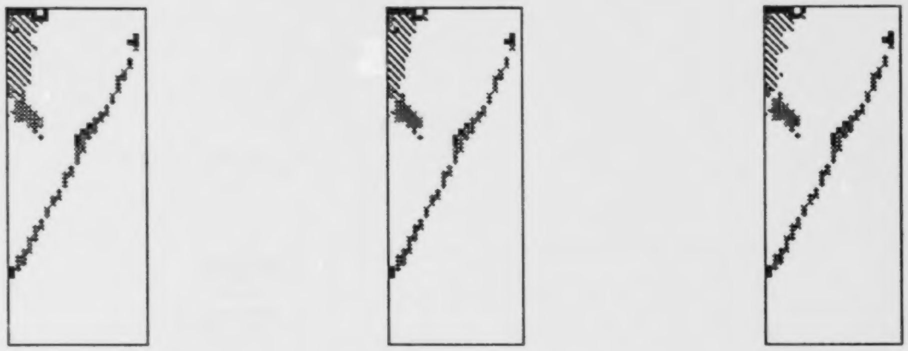
Although losses are highly variable around the U.S. coastline, the most important estimates are those for the nation as a whole. Simulations for 98 sites are planned, but for this initial analysis an unbiased subsample of 46 sites has been used. These sites represent a broad spectrum of temperate and subtropical coastal types, with varying tidal ranges, subsidence and accretion rates, fetches, and degrees of development (Table 1).

The percent coverage of the coastline with these 46 sites was used to estimate the initial area of wetlands, as well as the areas projected to be lost under the different sea-level scenarios. For example, the 29 sites in the mid-Atlantic subsample represent 8.62% of the area of the Mid Atlantic as defined in this study; the reciprocal of that value yields a transformation factor of 11.6, which was used to scale the subsample results to the entire Mid Atlantic. These calculations yield a national estimate of 13,145 mi^2 of coastal wetlands in 1986 (the time of Landsat coverage for the respective sites), compared to the estimate of 14,723 for comparable wetlands as reported by Titus and Green in this volume. (The wetlands for the mid-Atlantic and West coasts are underestimated in this initial study.)

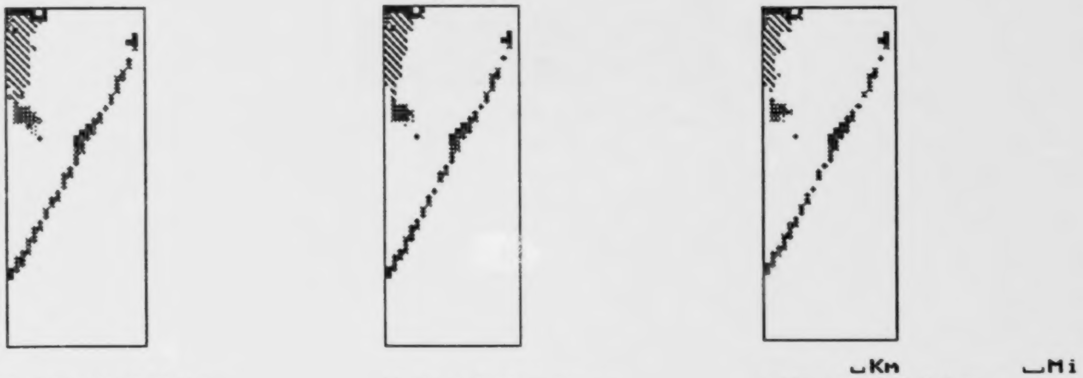
In Figure 8 the independent variable, time, has been replaced by sea level, making the ordinate more general but causing it to be expressed on an exponential scale. Mindful of the nonlinearity, saltmarshes are seen to expand initially and then decline by approximately 2,000 mi^2 with a 0.1-m rise in sea level in all three protection scenarios; this decline is due to the predicted rapid loss of saltmarshes in Louisiana and the rest of


Surf City
Ship Bottom
Beach Haven

A Present conditions B Protected, 14 cm C Protected, 0.5 m



D Protected, 1.0 m E Protected, 2.0 m F Protected, 3.0 m



G Unprotected, 1.0 m H Unprotected, 2.0 m I Unprotected, 3.0 m

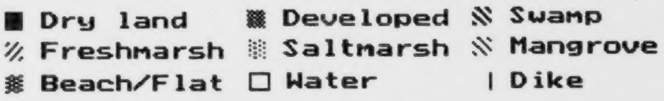

■ Dry land
▩ Developed
▧ Swamp
▨ Freshmarsh
░ Saltmarsh
▧ Mangrove
▩ Beach/Flat
□ Water
| Dike

Figure 4. Maps of the Long Beach Island, New Jersey, site showing present conditions and predicted conditions for the year 2100, with and without residential and commercial developments protected and with sea levels as indicated. Note the loss of marshes with the 0.5-m scenario.

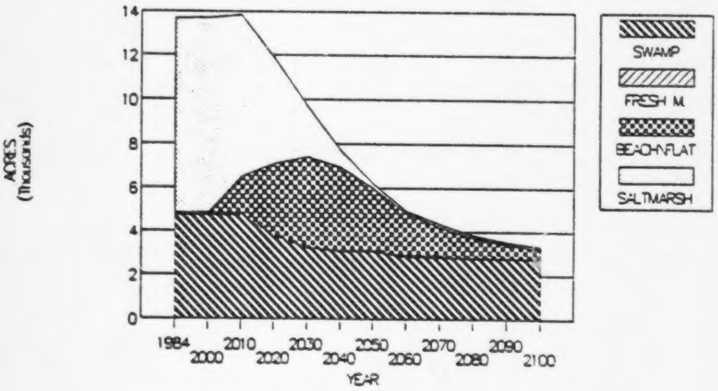
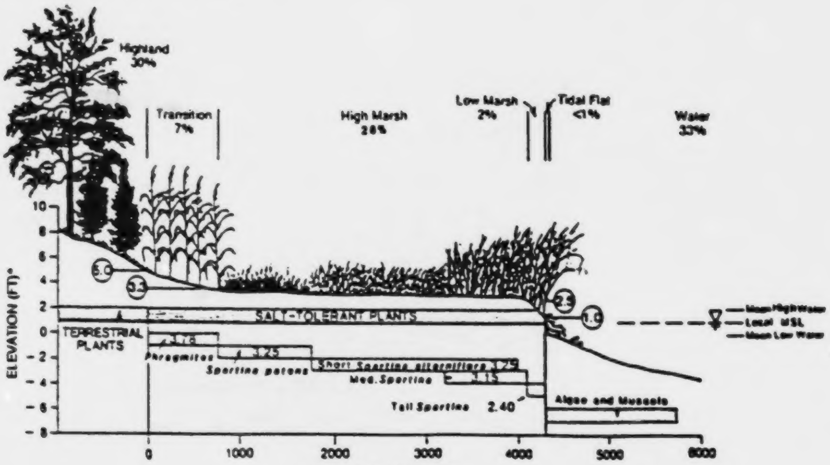


Figure 5. Changing areas of wetlands at the Long Beach, New Jersey, site with a 1-m sea level rise.

COMPOSITE TRANSECT OF THE TUCKERTON MARSH
(Tidal Range = 2.0 ft)


Highland
30%
Transition
7%
High Marsh
28%
Low Marsh
2%
Tidal Flat
<1%
Water
33%
10
8
6
4
2
0
-2
-4
-6
-8
ELEVATION (FT)*
5.0
3.3
2.5
1.0
SALT-TOLERANT PLANTS
TERRESTRIAL PLANTS
1.76
Phragmites
3.25
Spartina patens
Short Spartina alterniflora 3.79
Med. Spartina
3.15
Tall Spartina
2.40
Algae and Mussels
Mean High Water
Local MSL
Mean Low Water
0
1000
2000
3000
4000
5000
6000
TYPICAL DISTANCE (FT)

* *Elevations are relative to the 1929 NGVD sea level.*

Figure 6. Composite transect of the Tuckerton Marsh at the Long Beach, New Jersey, site (Kana et al., 1989).

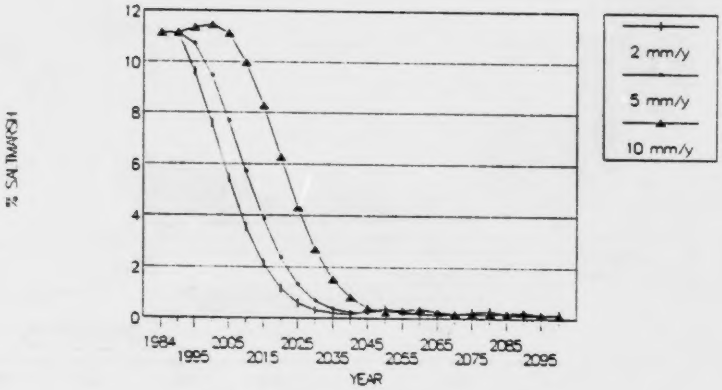


Figure 7. Sensitivity of predictions to different accretion rates for low marsh at Long Beach, New Jersey site.

Table 1. Study site locations, tidal range, subsidence, sedimentation and accretion rates, and fetch for the sites used in this initial study.

Site		Latitude	Longitude	Oceanic Tide m	Inland Tide m	Subsidence mm/yr	Sedimentation mm/yr	Accretion mm/yr	Fetch km
NORTHEAST									
MEROCKLA.	Rockland	44 07'30	69 07'30	2.8956	2.8956	1	0.20	2.0	3
MAMARBLE.	Marblehead	42 37'30	70 52'30	2.7737	0	1.7	0.20	2.0	0
MAWESTPO.	Westport	41 37'30	71 07'30	0.9144	0.9144	1.5	0.20	2.0	1
RIWATCHH.	Watch Hill	41 22'30	71 52'30	0.7924	0.7924	0.6	0.20	2.0	1
CNBRIDGE.	Bridgeport	41 15'	73 15'	2.0726	2.0726	0.9	0.20	2.0	1
MID ATLANTIC									
NYPATCHO.	Patchogue	40 52'30	73 07'30	0.7924	0.1828	1.5	0.20	2.0	6
NJLONGBE.	Long Beach	39 45'	74 15'	0.9144	0.3048	2.7	0.50	5.0	3
DEREHOBA.	Rehoboth B.	38 45	75 07'30	0.3657	0.0609	1.9	0.20	2.0	4
MDEASTON.	Easton	38 52'30	76 07'30	0	0.3048	2.4	0.20	2.0	1
MDELKTON.	Elkton	39 37'30	76 00'	0	0.7924	2.1	0.20	2.0	2
VABLOXOM.	Bloxom	37 52'30	75 37'30	1.0972	1.0972	1.9	0.20	2.0	1
VANEWPOR.	Newport News	37 07'30	76 30'	0.762	0.8534	3.1	0.50	5.0	5
SOUTH ATLANTIC									
NCENGELH.	Engelhard	35 45'	76 07'30	0	0	0.6	0.20	2.0	2
NCLONGBA.	Long Bay	35 00'	76 30'	0.9144	0.6096	0.6	0.50	5.0	4
NCWILMIN.	Wilmington	34 15'	78 00'	1.1582	1.1887	0	0.20	2.0	2
SCCHARLE.	Charleston	80 00'	30 00'	1.5849	0.9753	2.2	0.50	5.0	2
SCHILTON.	Hilton Head	32 22'30	80 52'30	2.0421	2.286	1.8	0.50	5.0	2
GASEAISL.	Sea Island	31 22'30	81 22'30	1.8501	2.0421	1.8	1.00	10.0	3
FLSTAUGU.	St Augustine	30 07'30	81 30'	1.3716	1.3716	0.7	0.20	2.0	0
FLCAPECA.	Cape Canaveral	28 30'	80 45'	1.0668	0	1	0.20	2.0	5
SOUTH & WEST FLORIDA									
FLMIAMI.	Miami	25 52'30	80 15'	0.762	0.6096	1.1	0.20	2.0	3
FLKEYWES.	Key West	24 37'30	81 52'30	0.3962	0.3962	1	0.20	2.0	0
FLEVERGL.	Everglades City	26 00'	81 22'30	0.6096	1.0668	1	0.50	5.0	2
FLVENICE.	Venice	27 15'	82 30'	0.64	0.64	1.1	0.20	2.0	0
FLPORTRI.	Port Richey	28 30'	83 45'	0.6096	0.6096	0.7	0.50	5.0	15
FLSNIPEI.	Snipe Is.	30 07'30	83 52'30	0	0.6096	0.7	0.50	5.0	20
NORTH GULF (EXCL. LA)									
FLFTGADS.	Fort Gadsden	30 00'	85 07'30	0	0.6400	1.2	0.20	2.0	2
FLAPALAC.	Apalachicola	29 45'	85 07'30	0.7010	0.3992	1.2	0.20	2.0	8
FLSTJOSE.	St Joseph	29 52'30	85 30'	0.3992	0.3992	0.7	0.20	2.0	7
FLHOLLEY.	Holley	30 30'	87 07'30	0	0.4572	1.2	0.20	2.0	6
MSGULFPO.	Gulfport	30 30'	89 15'	0	0.6096	1.2	0.20	2.0	20
MSPASSCH.	Pass Christian	30 22'30	89 15'	0.3048	0	1.2	0.20	2.0	20
TXALLIGA.	Alligator Hole	29 52'30	94 15'30	0.3048	0	12	0.50	5.0	0
TXPALACI.	Palacios	28 45'	96 15'	0.3048	0.3048	2.8	0.20	2.0	6
TXPORTLA.	Portland	27 52'30	97 22'	0	0	2.8	0.20	2.0	4
TXGREENI.	Green Is.	26 30'	97 22'	0.3048	0.1524	3.9	0.20	2.0	7
LOUISIANA									
LAMAINPA.	Main Pass	29 22'30	89 15'	0.1524	0.1524	9.3	0.50	5.0	2
LALULING.	Luling	29 52'30	90 15'	0	0.0762	8.5	0.50	5.0	1
LABARATA.	Barataria	29 45'	90 22'30	0	0.1524	9.3	0.50	5.0	4
LAGOLDME.	Golden Meadow	29 30'	90 22'30	0	0.0762	9.3	1.00	10.0	0
LAPELICA.	Pelican Pass	29 15'	90 22'30	0.3048	0.3048	13.8	0.50	5.0	0
LALMISER.	Lake Misere	30 07'30	93 00'	0	0	8.5	0.20	2.0	6
LAGRANDC.	Grand Chenier	29 52'30	93 00'	0.6096	0.6096	8.5	0.50	5.0	0
WEST									
CAALBION.	Albion	39 15'	123 52'30	1.2192	0	0	0.20	2.0	0
CAPTSAL.	Point Sal	35 00'	120 45'	1.2192	1.2192	0	0.20	2.0	0
CABENICI.	Benicia	38 15'	122 22'30	1.2192	0.6096	1.68	1.00	10.0	0
CASANQUE.	San Quentin	38 00'	122 30'	0	1.2192	0.1	0.20	2.0	8
ORYAQUIN.	Yaquina	44 45'	124 07'30	1.8288	1.8288	-1	0.20	2.0	2
WAANACOR.	Anacortes	48 45'	122 45'	1.524	1.524	0.2	0.20	2.0	10
WATACOMA.	Tacoma	47 30'	122 30'	3.3528	2.4384	0.8	0.20	2.0	4

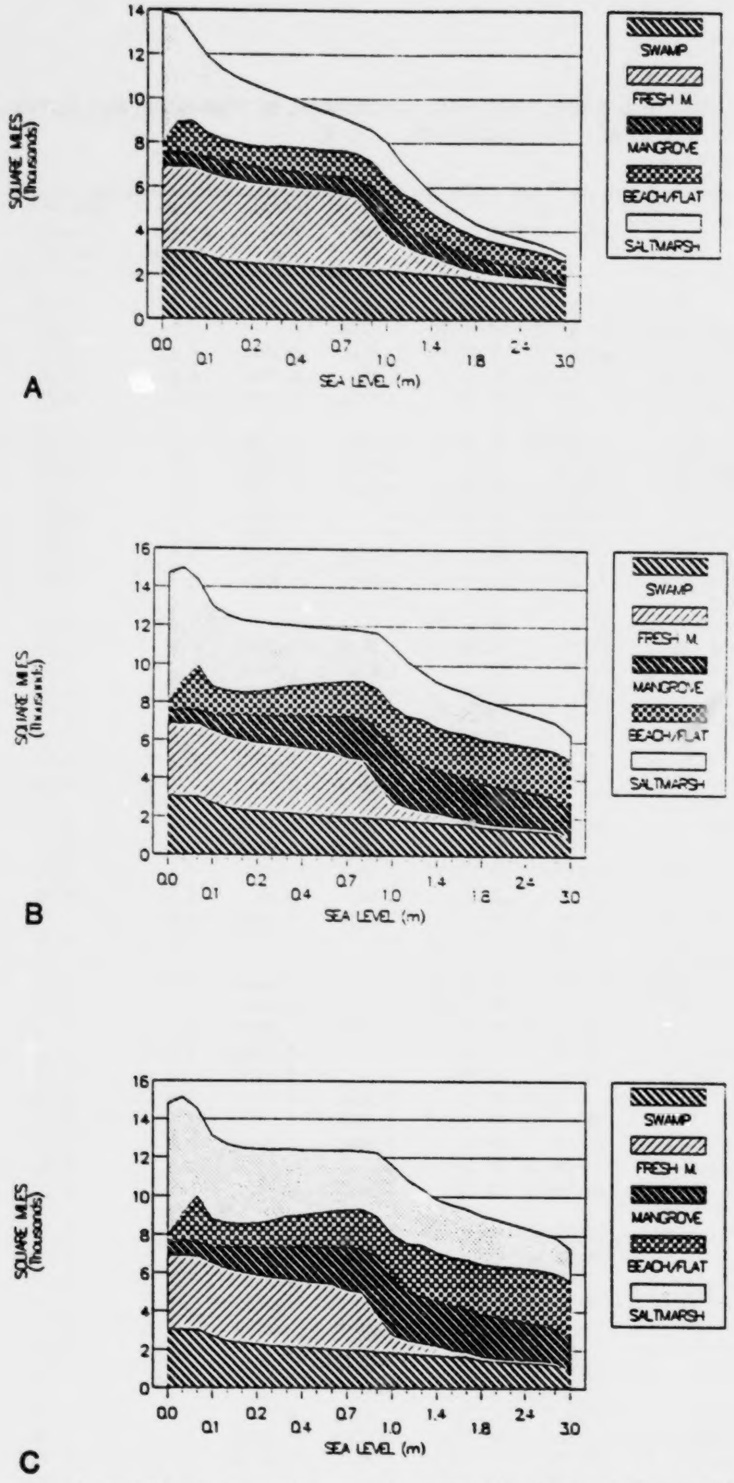


Figure 8. Changing areas of wetlands of the contiguous U.S. coast with global warming and (A) with all dry lands protected, (B) with existing developed areas protected, and (C) with no protection.

the northern Gulf of Mexico. With all dry land protected, saltmarshes will continue to decline until almost all disappear with a 3-m rise, and mangrove swamps will not change significantly in area; with only developed areas protected, the decline of saltmarshes will be much less pronounced and mangrove swamps will increase significantly; with no protection, saltmarshes will decline even less rapidly. With a 1-m rise by the year 2100, and with all developed areas being protected from inundation, 8,673 mi^2 or approximately 65% of the coastal wetlands of the contiguous United States will be lost (Table 2).

REGIONAL TRENDS

Mid-Atlantic

The Mid-Atlantic region (Figure 2) has moderate tidal ranges, extensive barrier island and estuarine systems, and adjacent lowlands that could be colonized by saltmarshes if not protected by engineering structures. Currently, vegetated wetlands cover approximately 746 mi^2, as estimated in this study. Long Beach, New Jersey, typifies the barrier island systems and has already been examined (Figures 3,4). The regional response for the total protection scenario (Figure 9) would consist of a gradual decline of wetlands, with tidal flats replacing saltmarshes.

Southeast

Vegetated wetlands cover 11,735 mi^2 in the southeastern states, from North Carolina to Texas; this is 89% of the vegetated wetlands of the contiguous United States. Therefore, the responses of the southeastern wetlands to sea level rise (Figure 10) are similar to those presented for the United States. Coastal responses have been considered separately for several subregions, with examination of sites representing estuarine, deltaic, barrier island, and subtropical carbonate platform environments.

South Atlantic Coastal Plain. This region (Figures 11, 12) is characterized by relatively high tidal ranges and by extensive low terraces representing Pleistocene barrier island systems (such as the sea islands of South Carolina and Georgia). Wetlands are well developed, especially near major rivers where sedimentation and accretion are highest; at present they cover 3,813 mi^2. Because of the high tidal ranges and the availability of lowlands for colonization, these wetlands will be more persistent in the face of rising sea level compared with other U.S. coastal areas (Figure 13). Mangroves can be expected to spread into the more southerly sites if temperatures increase.

Charleston, South Carolina. This historic town is at the confluence of several estuaries with large tidal ranges and extensive marshes. Near the mouth of the harbor Sullivan's Island (celebrated in The Gold Bug by Edgar Allen Poe) forms a barrier island with a well developed back-barrier marsh. The recent rediversion of the Santee River has decreased the high sedimentation that helped promote the historic growth of wetlands; however, assuming no change in historic trends, the model predicts a slight expansion of marshes onto dredge-fill areas by the year 2100 (Figure 14B). With a half-meter rise, most of the saltmarshes would be inundated and converted to tidal flats exposed only at low tide (Figure 14C); increasing sea level stands would lead to widespread inundation of low-lying areas adjacent to the rivers (Figure 14D-F). The 1-meter scenario yields an estimate of 47% loss of saltmarsh by 2075, which is quite close to the estimate of 51% by 2075 reported by Kana et al. (1988), based on detailed transects.

Sea Island, Georgia. The wetlands of the Georgia Sea Islands have been studied intensively for many years. Marshes are very well developed in the region, due to a combination of high tidal ranges and high sedimentation rates. The site covers two topographic quadrangles, including the communities of Sea Island, St. Simons Island, and part of Brunswick on the mainland (Figure 15). There is no appreciable change in wetlands and adjacent lowlands until almost a 1-meter rise, due to the existence of a 2-meter tidal range (with marshes occupying the upper meter) and a low Pleistocene terrace. With a 1-meter rise and a significantly warmer climate, mangroves would spread onto the low terrace and the marsh would begin to break up. By two meters the community of

Table 2. Regional and national estimates of losses of coastal marshes and swamps by the year 2100 (in square miles) for the baseline case and four sea-level scenarios, considering also three levels of shoreline protection: total protection of all dry land, standard protection of areas with residential and commercial development, and no protection. Results are based on simulations using unbiased samples encompassing variable percentages of total area of respective coasts.

Region	Sampled	Baseline	0.5 m	1 m	2 m	3 m
Northeast	3.36%					
Total			88	93	100	188
Standard		39	55	58	33	434
No			27	8	(67)	335
Mid Atlantic	11.6%					
Total			485	520	625	705
Standard		(39)	201	341	429	574
No			120	180	361	465
South Atlantic	10.07%					
Total			2,295	2,422	2,542	2,736
Standard		(59)	1,438	1,669	1,812	2,227
No			1,313	1,516	1,606	2,044
S & W Florida	10.71%					
Total			623	829	1,020	1,300
Standard		(157)	92	157	165	665
No			63	122	120	631
Louisiana	13.66%					
Total			2,450	3,742	4,758	4,801
Standard		2,271	2,368	2,732	4,686	4,776
No			2,345	3,732	4,685	4,778
Other N. Gulf	13.04%					
Total			530	1,301	1,121	1,170
Standard		270	396	932	994	1,079
No			360	918	982	1,070
West*	4.87%					
Total			37	36	39	53
Standard		(71)	(286)	(440)	(651)	(761)
No			(332)	(518)	(791)	(843)
United States						
Total			6,511	8,673	10,206	10,953
Standard		2,254	4,263	6,441	7,423	8,994
No			3,904	6,046	6,892	8,480

* subject to correction

the northern Gulf of Mexico. With all dry land protected, saltmarshes will continue to decline until almost all disappear with a 3-m rise, and mangrove swamps will not change significantly in area; with only developed areas protected, the decline of saltmarshes will be much less pronounced and mangrove swamps will increase significantly; with no protection, saltmarshes will decline even less rapidly. With a 1-m rise by the year 2100, and with all developed areas being protected from inundation, 8,673 mi^2 or approximately 65% of the coastal wetlands of the contiguous United States will be lost (Table 2).

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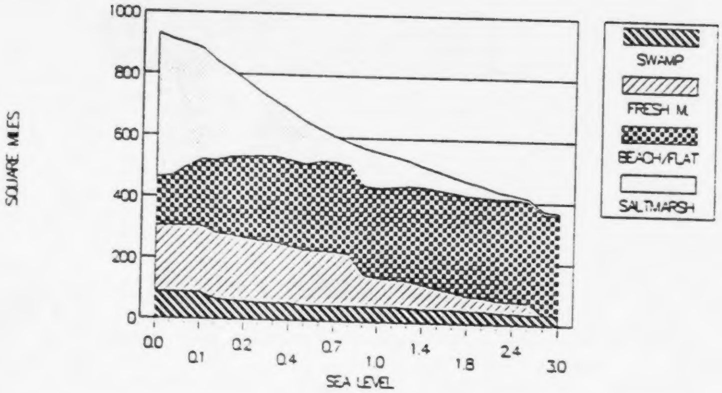


Figure 9. Changing areas of mid-Atlantic coastal wetlands with global warming and sea level rise, and with existing developed areas protected.

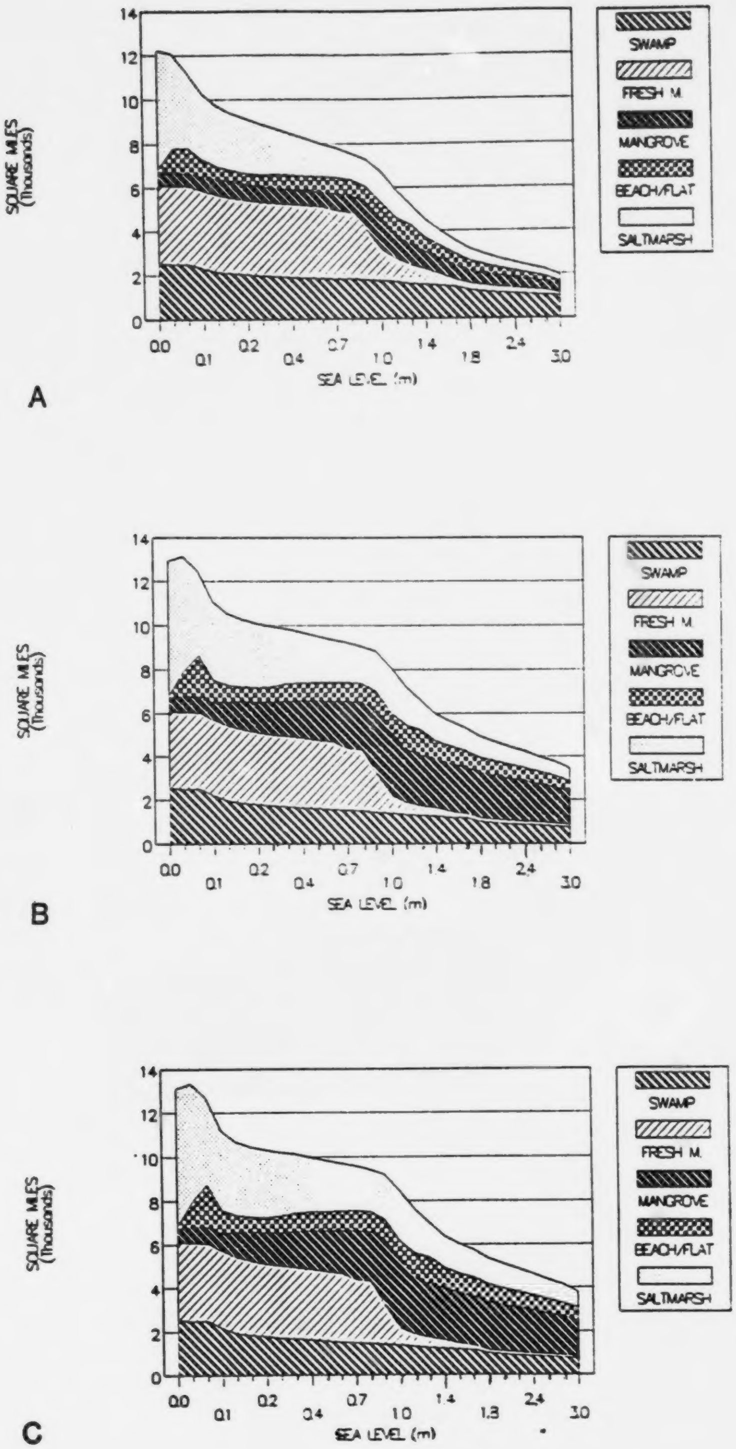


Figure 10. Changing areas of coastal wetlands of the southeast with global warming and (A) with all dry lands protected, (B) with existing developed areas protected, and (C) with no protection.

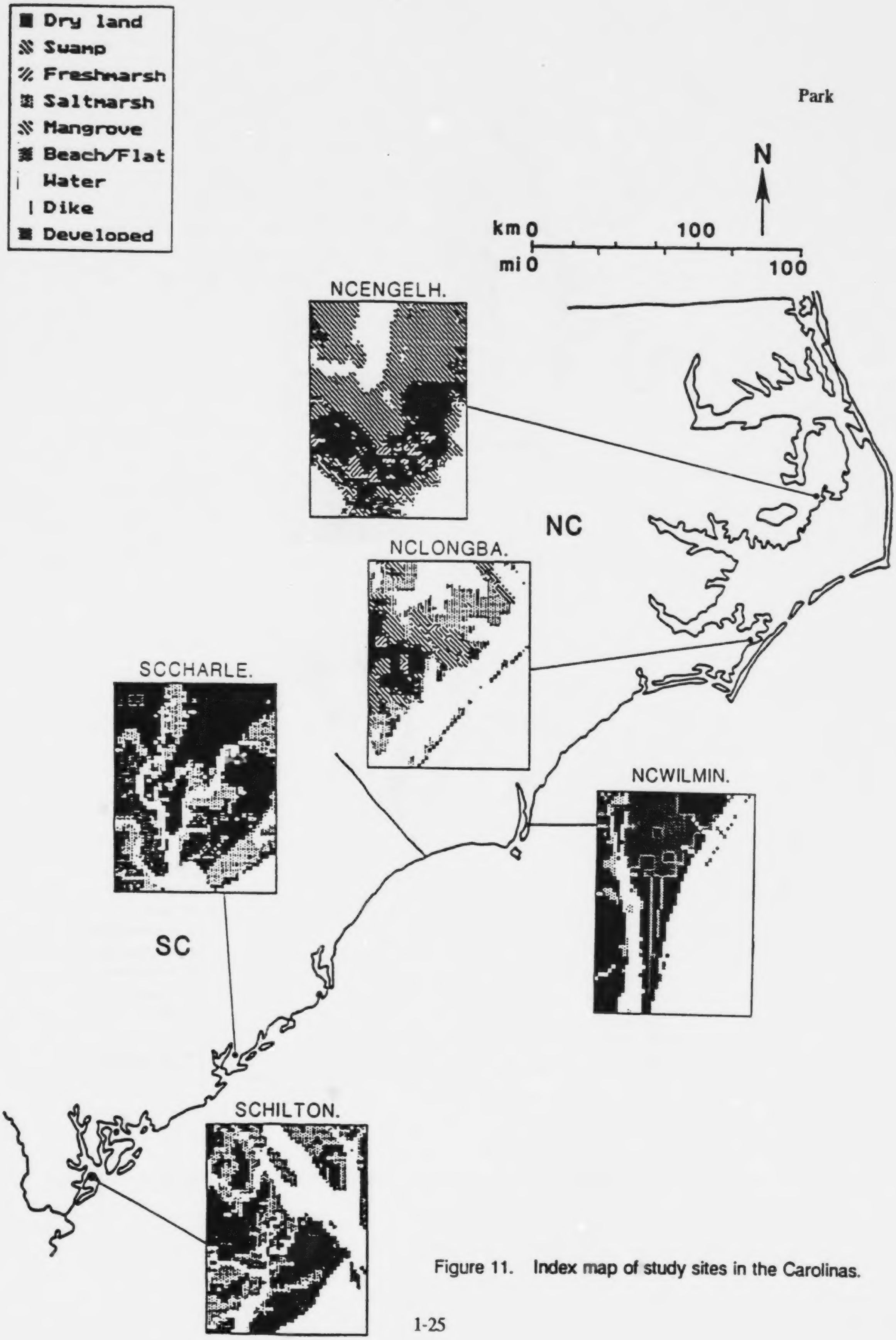

Dry land
Swamp
Freshmarsh
Saltmarsh
Mangrove
Beach/Flat
Water
Dike
Developed
N
km 0
100
mi 0
100
NCENGELH.
NC
NCLONGBA.
SCCHARLE.
NCWILMIN.
SC
SCHILTON.

Figure 11. Index map of study sites in the Carolinas.

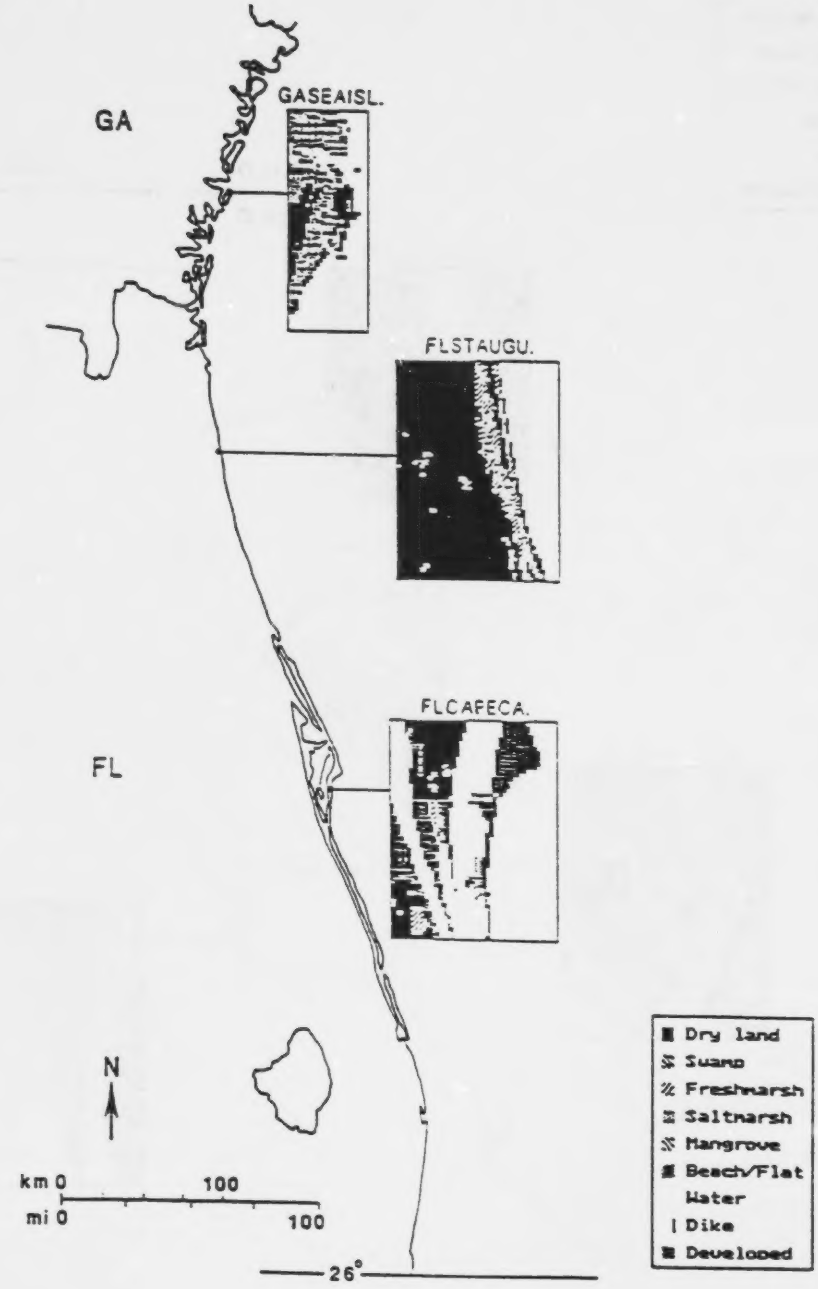

GASEAISL.
GA
FLSTAUGU.
FLCAFECA.
FL
N
km 0
100
mi 0
100
26°
Dry land
Swamp
Freshmarsh
Saltmarsh
Mangrove
Beach/Flat
Water
Dike
Developed

Figure 12. Index map of study sites in Georgia and Northeastern Florida.

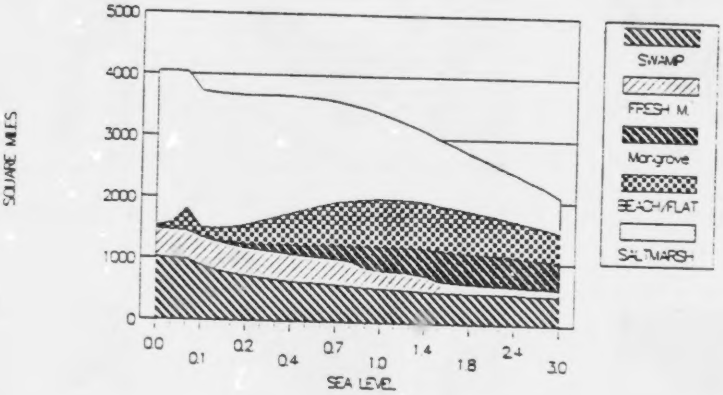
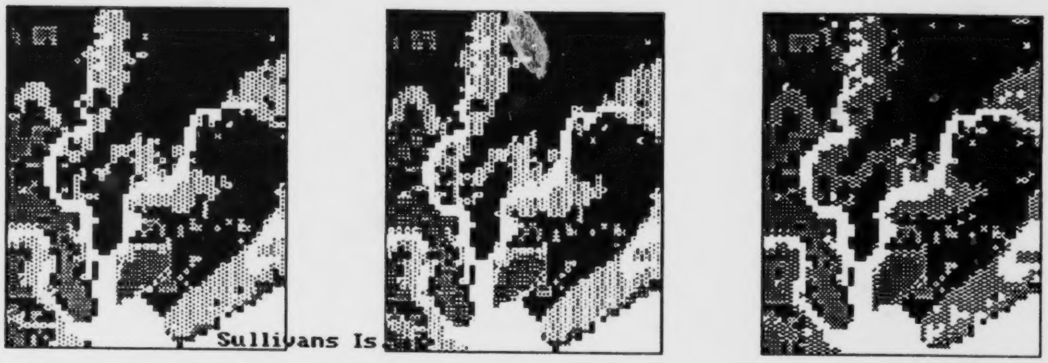
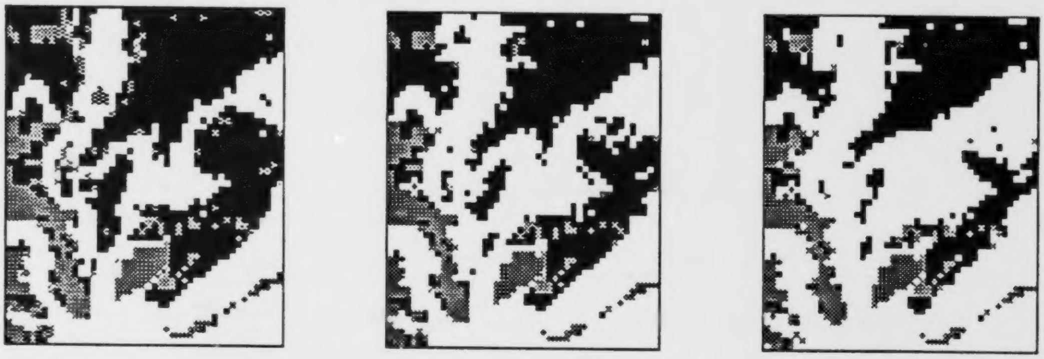


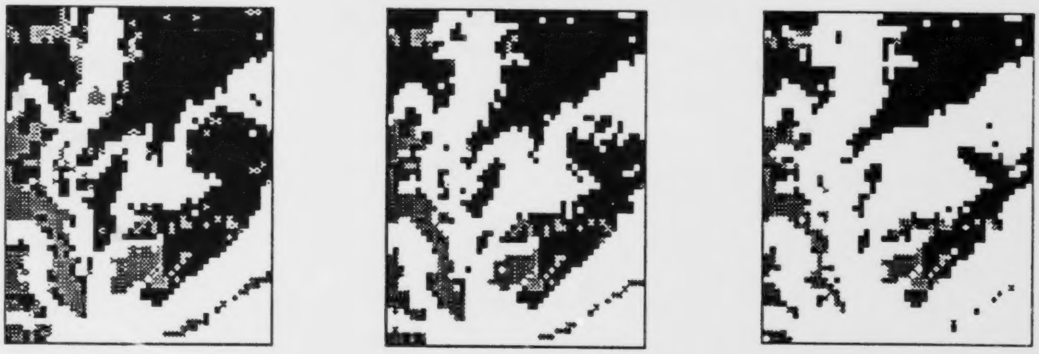
Figure 13. Changing areas of South Atlantic coastal wetlands with global warming and sea level rise, and with existing developed areas protected.



A Present conditions B Protected, 14 cm C Protected, 0.5 m



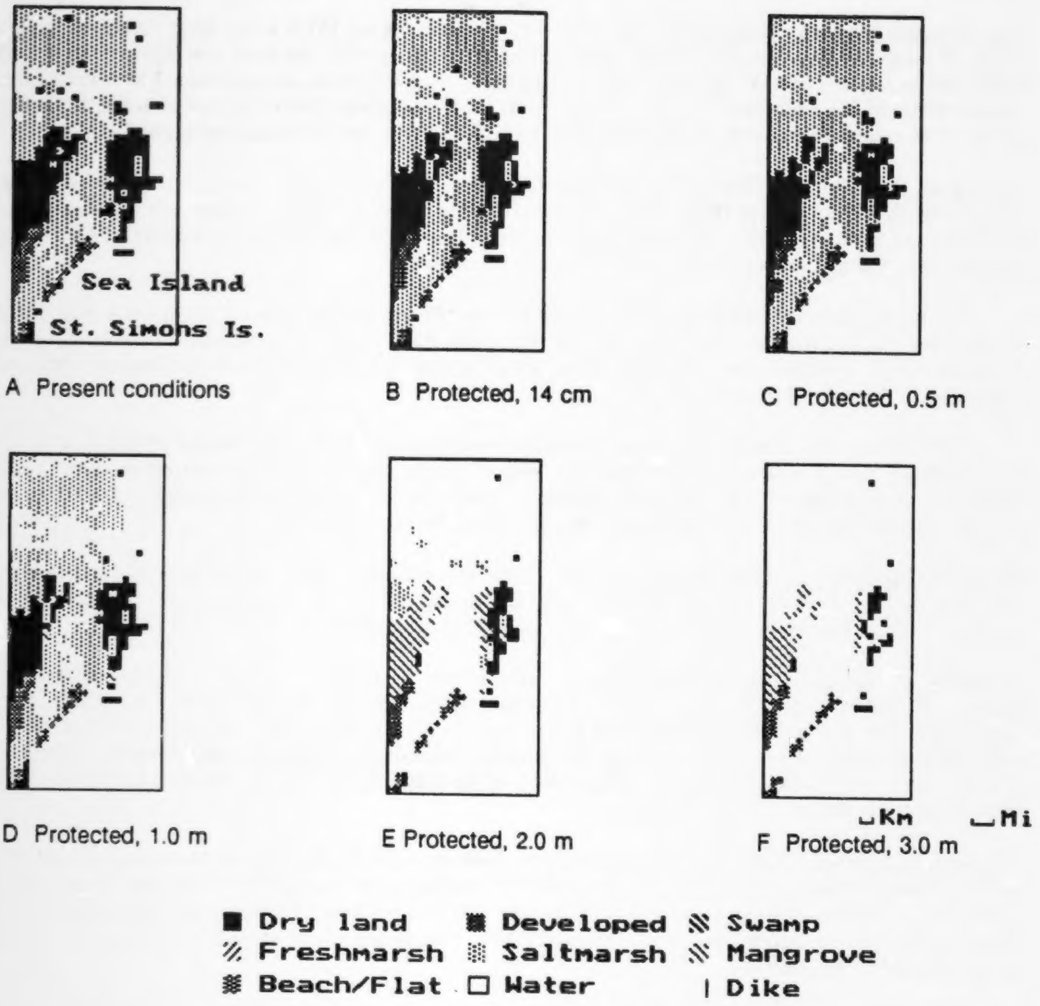
D Protected, 1.0 m E Protected, 2.0 m F Protected, 3.0 m



G Unprotected, 1.0 m H Unprotected, 2.0 m I Unprotected, 3.0 m

■ Dry land ▩ Developed ▧ Swamp
▨ Freshmarsh ░ Saltmarsh ▧ Mangrove
▩ Beach/Flat ☐ Water | Dike

Figure 14. Maps of the Charleston, South Carolina, site showing present conditions and predicted conditions for the year 2100, with and without residential and commercial developments protected and with sea levels as indicated. Note the widespread inundation of lowlands.


Sea Island
St. Simons Is.
Km
Mi
Dry land
Developed
Swamp
Freshmarsh
Saltmarsh
Mangrove
Beach/Flat
Water
Dike

A Present conditions

B Protected, 14 cm

C Protected, 0.5 m

D Protected, 1.0 m

E Protected, 2.0 m

F Protected, 3.0 m

Figure 15. Maps of the Sea Island, Georgia, site showing present conditions and predicted conditions for the year 2100, with protection of residential and commercial developments and sea levels as indicated. Note the persistence of the marshes and the eventual spread of mangroves.

Sea Island would either be a diked enclave in the sea or a largely inundated and eroded shoal area. By three meters the only appreciable dry land left, other than in developed areas, would be the Pleistocene beach ridge on Little St. Simons Island.

Southern and Western Coasts of Florida. Southern Florida (Figure 16) is a low-lying carbonate platform and string of coral-reef keys that developed during interglacial epochs when sea level was higher than it is today. A slight rise in sea level would inundate this area again. The Everglades are maintained as a broad freshwater marsh by runoff from the interior; the saltwater wetlands are dominated by mangrove swamps which occur over a narrow elevational range due to the low tidal range. This initial study estimated the area of vegetated wetlands.

Everglades City, Florida. This site is characterized by mangrove swamps and low beach ridges, with Everglades on the slightly higher ground (Figure 17). As shown by the maps, mangrove swamps would actually increase in area with sea level rise as the low beach ridges are inundated by a 2-meter rise in sea level. With more than a 2-meter rise, the mangroves would gradually decrease in area.

The west coast north of subtropical southern Florida (Figure 18) has a very gradual slope offshore, marshes on the open coast, a low tidal range, and a low terrace along the coast. Consequently, it too is quite vulnerable to sea level rise. Furthermore, with moderating temperatures, the entire region would become subtropical and mangrove swamps would spread north.

This initial study estimated the area of vegetated wetlands in southern and western Florida to be 1,869 mi^2. Considering the regional response (Figure 19), with a 1-meter sea level rise all saltmarsh would be lost, and mangroves would expand onto adjacent lowlands at the expense of freshwater swamps. At higher sea level stands, both the mangrove and freshwater swamps would be gradually lost.

Northern Gulf Coast Excluding Louisiana. The northeastern Gulf Coastal Plain (Figure 20) is characterized by low tidal ranges, generally narrow barrier islands and spits, and poorly developed low terraces; consequently, wetlands are not extensive, except in river deltas, and they are vulnerable to sea level rise.

Apalachicola Bay and Fort Gadsden, Florida. This is the last relatively undisturbed bay and estuary in the eastern Gulf of Mexico. With a 1-meter rise in sea level St. Vincents Island would be inundated, the narrow barrier island would be breached in several places, and the Apalachicola River estuary would exceed 2 miles in width (Figure 21D). The swamp would be gradually inundated and mangroves would replace saltmarsh as the dominant vegetated saltwater wetland, thus converting the area into subtropical estuary. At higher stands of sea level even more wetlands would be lost.

Gulfport, Mississippi. Gulfport and Long Beach are built on a low beach ridge on Mississippi Sound. The fetch is large enough that beach erosion can occur, and the elevation is low enough that with a half-meter rise and with protection of developed areas a lagoon would open up behind Long Beach (Figure 22C); without protection Long Beach would be lost with a 1-meter rise (Figure 22G). This is one of the most dramatic impacts on an urban area observed in the study.

With the exception of eastern Texas, which is a continuation of the chenier (old beach) plain of Louisiana, the coast of Texas (Figure 23) is characterized by higher terraces along the coast. These combined with the low tidal range will lead to an early loss of wetlands with sea level rise. At the present time high salinities in the Laguna Madre of South Texas prevent development of marshes and mangroves. This salinity control is not included in the model, so marshes may be over-represented in the lower sea level rise scenarios. Presumably with higher sea level there will be breaching of Padre Island and exchange with the open ocean so that salinity will not be a limiting factor in the maintenance of wetlands.

Considering the entire northern Gulf Coast other than Louisiana, this study estimates the present area of vegetated wetlands to be 1,218 mi^2. A striking pattern of saltmarsh loss would take place, with only a slight rise

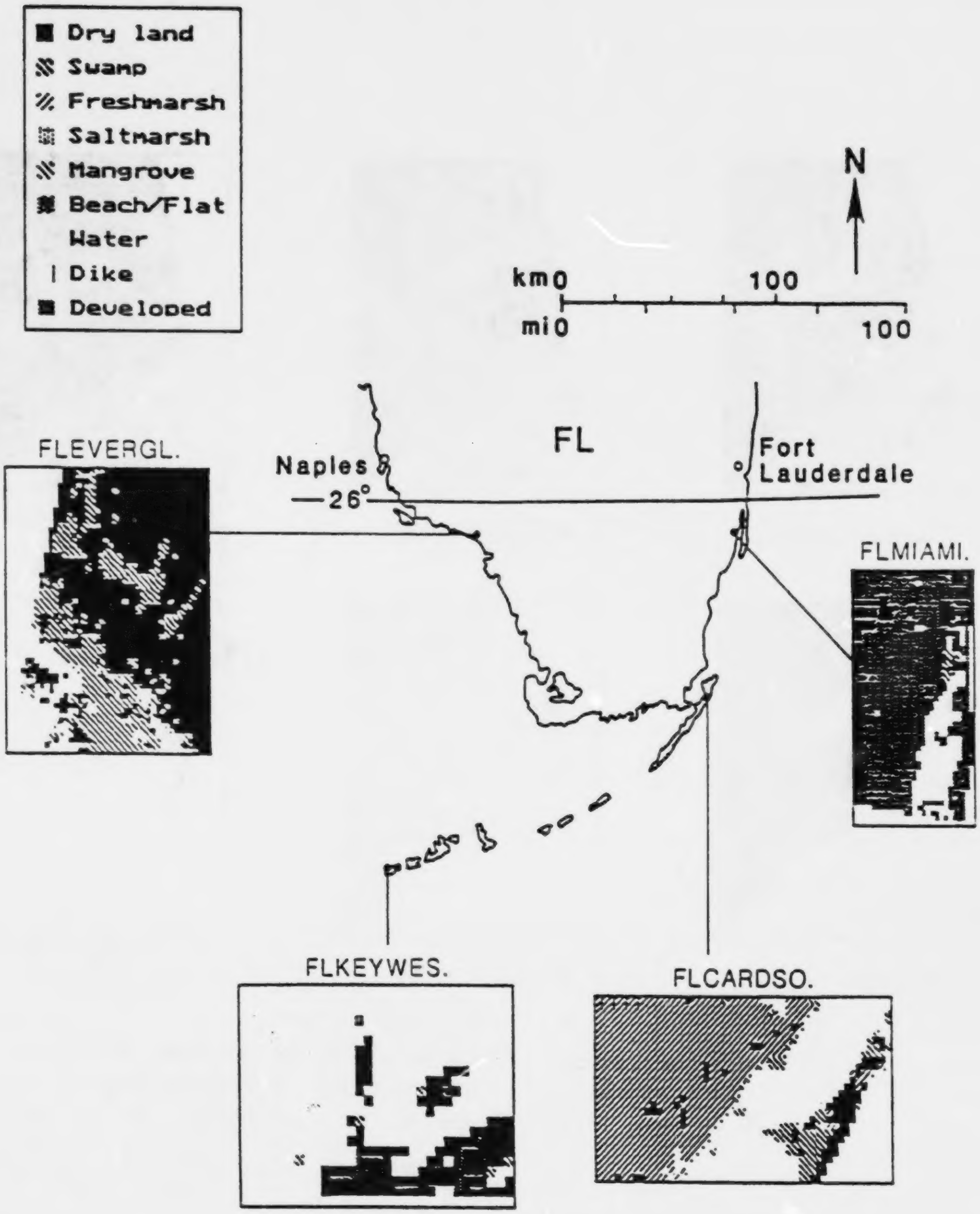
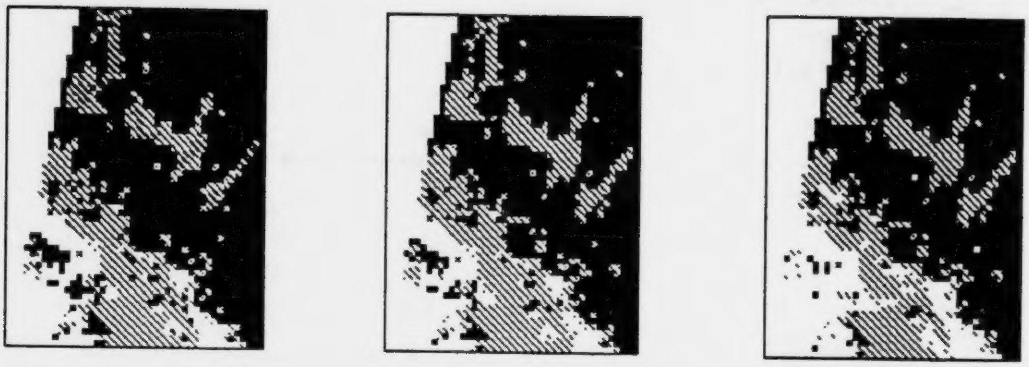

Dry land
Swamp
Freshmarsh
Saltmarsh
Mangrove
Beach/Flat
Water
Dike
Developed
N
km 0
100
mi 0
100
FL
Naples
26°
Fort Lauderdale
FLEVERGL.
FLMIAMI.
FLKEYWES.
FLCARDSO.

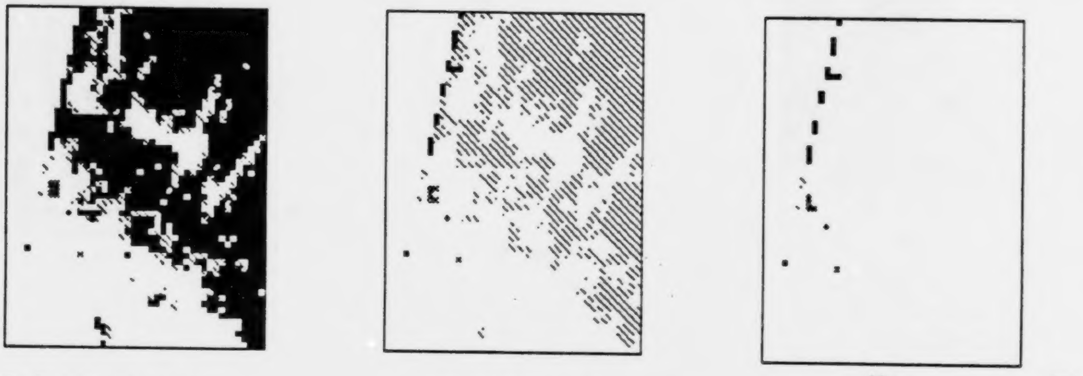
Figure 16. Index map of southern Florida sites.



A Present conditions

B Protected, 14 cm

C Protected, 0.5 m



D Protected, 1.0 m

E Protected, 2.0 m

F Protected, 3.0 m

■ Dry land ▩ Developed ▧ Swamp
▨ Freshmarsh ░ Saltmarsh ▧ Mangrove
▩ Beach/Flat ☐ Water | Dike

Figure 17. Maps of the Everglade City, Florida, site showing present conditions and predicted conditions for the year 2100 with protection of residential and commercial developments and with sea levels as indicated. Note the spread of mangroves onto the lowland and, at 3m, inundation of all but the beach ridge and town.

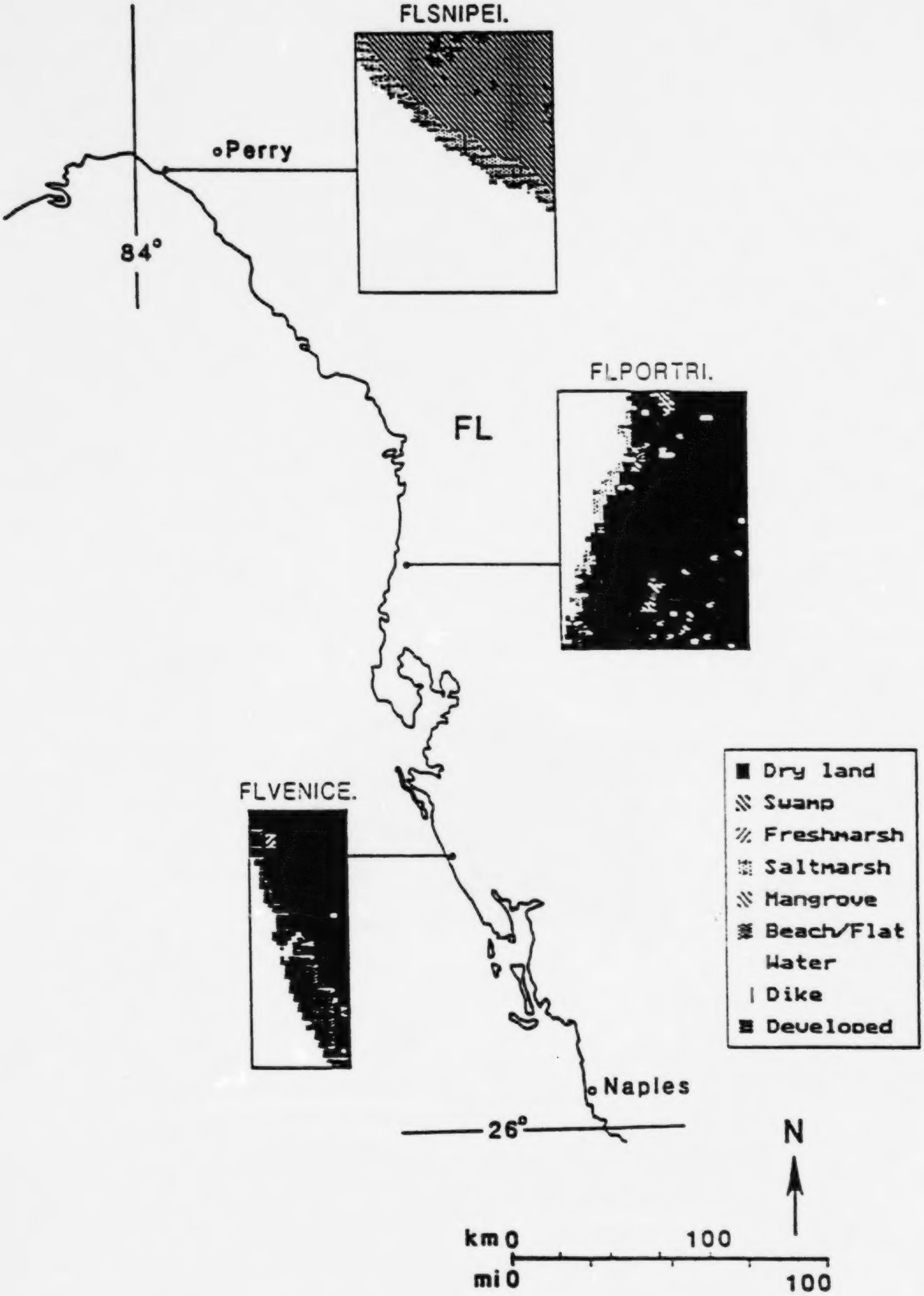

FLSNIPEI.
Perry
84°
FLPORTRI.
FL
FLVENICE.
Dry land
Swamp
Freshmarsh
Saltmarsh
Mangrove
Beach/Flat
Water
Dike
Developed
Naples
26°
N
km 0
100
mi 0
100

Figure 18. Index map of sites on the west coast of Florida.

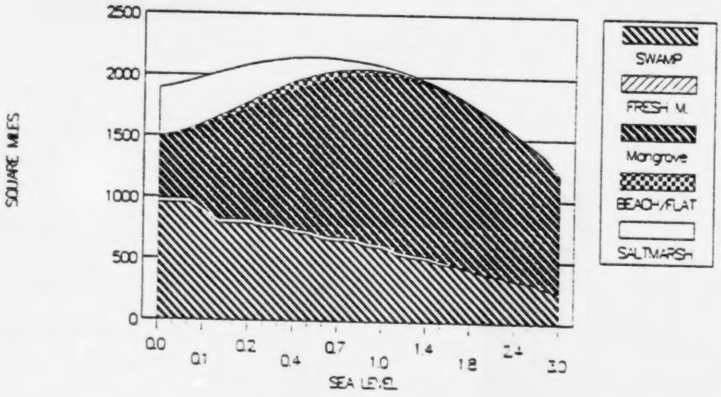


Figure 19. Changing areas of south and west Florida coastal wetlands with global warming and sea level rise, and with existing developed areas protected.

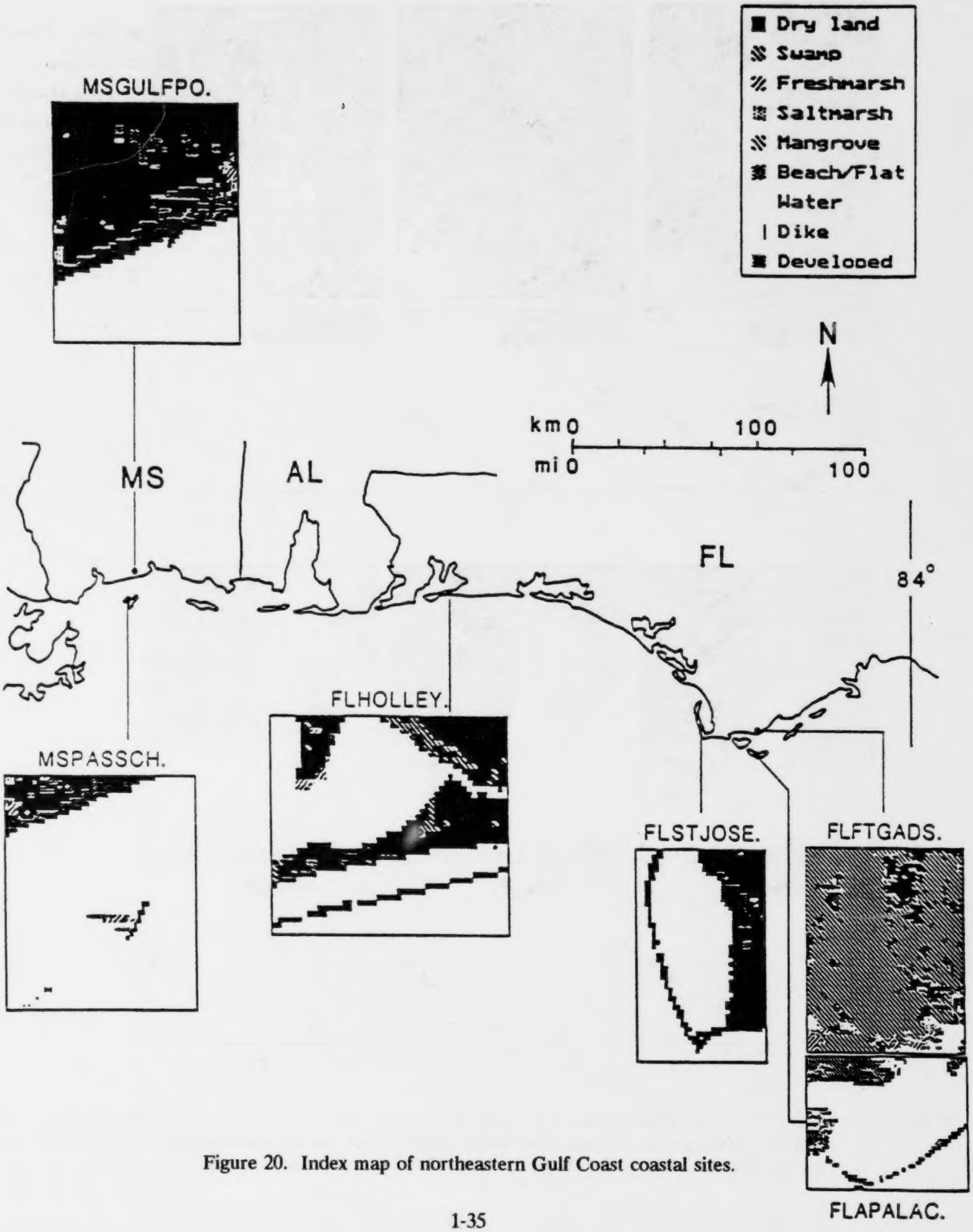

Dry land
Swamp
Freshmarsh
Saltmarsh
Mangrove
Beach/Flat
Water
Dike
Developed
MSGULFPO.
MSPASSCH.
FLHOLLEY.
FLSTJOSE.
FLFTGADS.
FLAPALAC.
MS
AL
FL
N
km 0
100
mi 0
100
84°

Figure 20. Index map of northeastern Gulf Coast coastal sites.

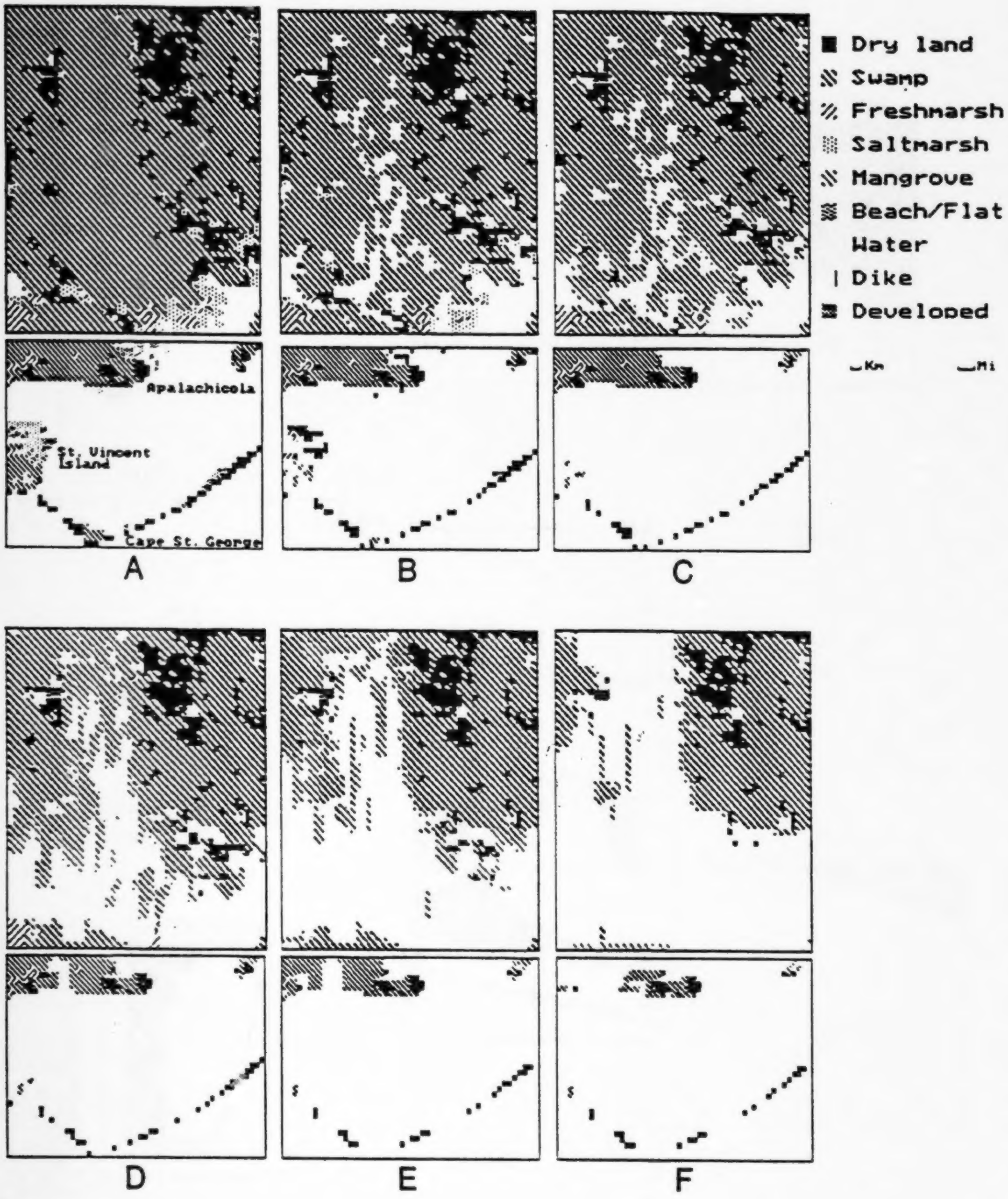
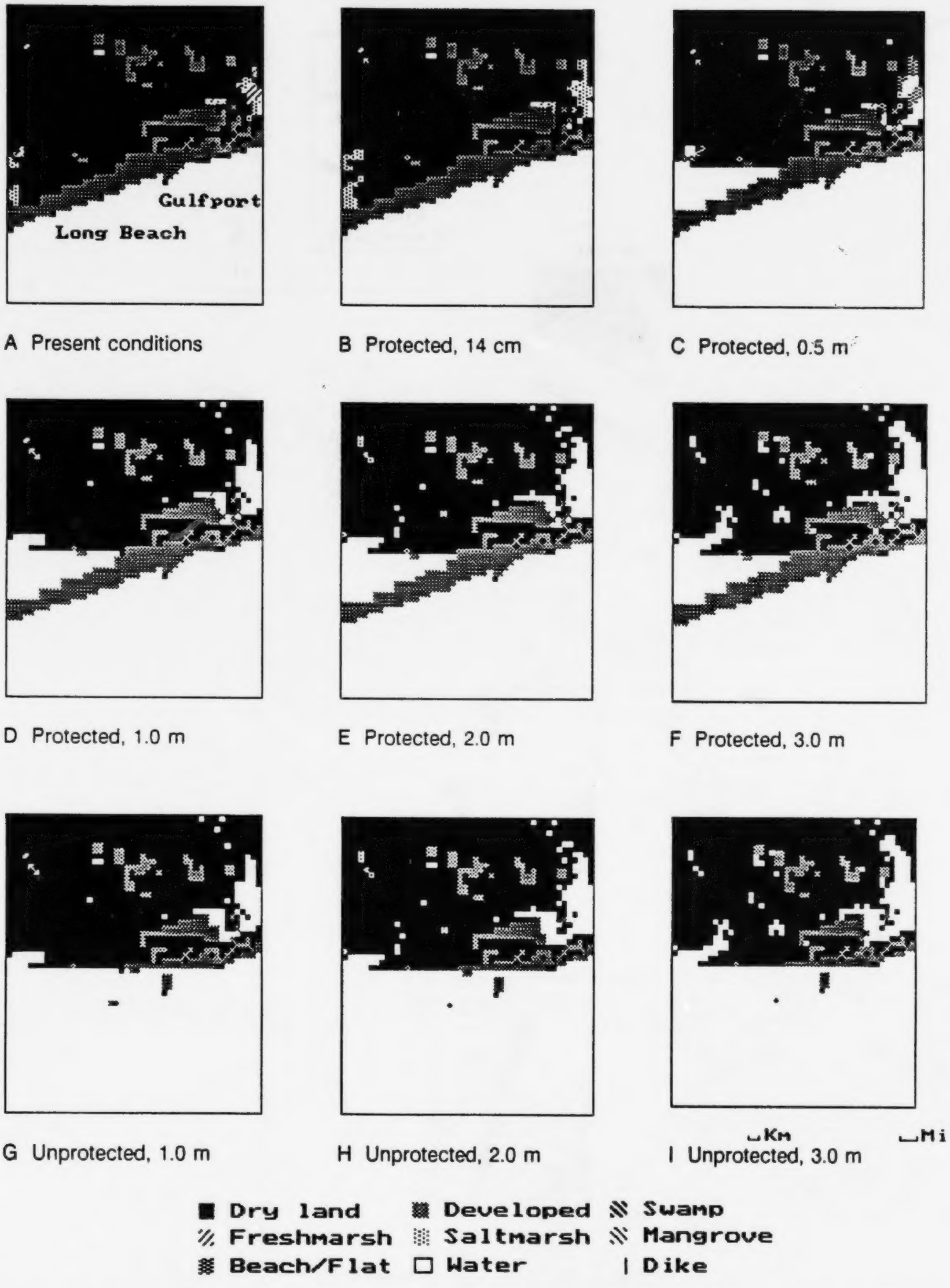

Dry land
Swamp
Freshmarsh
Saltmarsh
Mangrove
Beach/Flat
Water
Dike
Developed
Km
Mi
Apalachicola
St. Vincent Island
Cape St. George
A
B
C
D
E
F

Figure 21. Maps of the Apalachicola and Fort Gadsen, Florida, sites showing present conditions (A), and predicted conditions for the year 2100 with residential and commercial developments protected and with sea levels of 14-cm (B), 0.5-m (C), 1.0-m (D), 2.0-m (E), and 3.0-m (F).


Gulfport
Long Beach
Km
Mi
■ Dry land
▩ Developed
▧ Swamp
▨ Freshmarsh
▒ Saltmarsh
▧ Mangrove
▩ Beach/Flat
☐ Water
| Dike

A Present conditions

B Protected, 14 cm

C Protected, 0.5 m

D Protected, 1.0 m

E Protected, 2.0 m

F Protected, 3.0 m

G Unprotected, 1.0 m

H Unprotected, 2.0 m

I Unprotected, 3.0 m

Figure 22. Maps of the Gulfport, Mississippi, site showing present conditions and predicted conditions for the year 2100, with and without protection of residential and commercial developments and with sea levels as indicated. Note the complete inundation of Long Beach if unprotected.

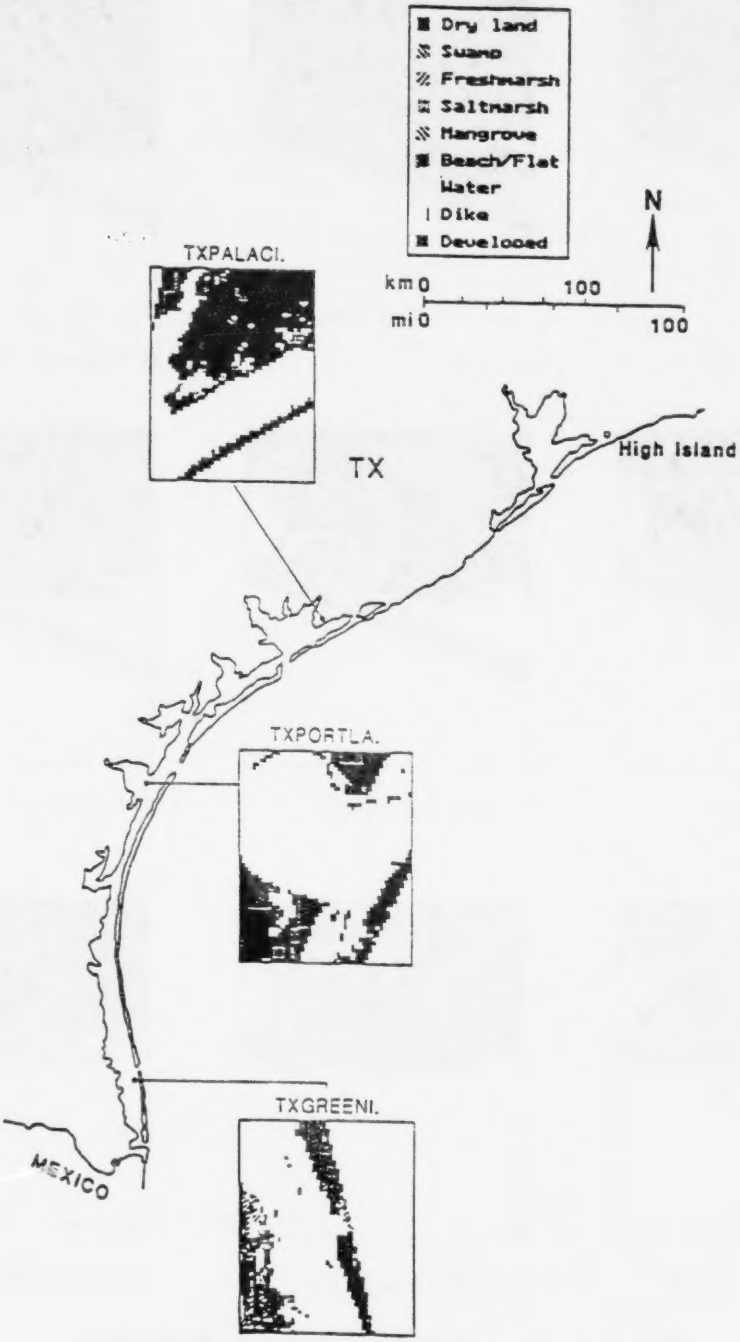

Dry land
Swamp
Freshmarsh
Saltmarsh
Mangrove
Beach/Flat
Water
Dike
Developed
N
km 0
100
mi 0
100
TXPALACI.
TX
High Island
TXPORTLA.
TXGREENI.
MEXICO

Figure 23. Index map of Texas sites.

in sea level (Figure 24); with a one-meter rise most freshwater marshes would be lost as well. With moderating climate saltmarshes would be replaced by mangroves, and the northern Gulf would become a subtropical coastal system.

Louisiana. A surprisingly similar response is predicted for this region (Figure 25). At present vegetated wetlands cover 4,835 mi^2. Tidal flats may initially expand as beaches, cheniers (old beaches), and dredge-fill areas are reclaimed by the sea; but saltmarshes will continue their rapid decline; mangroves would increase; and, prior to a 1-meter rise, most freshwater marshes would be lost (Figure 26). The pattern predicted for this region is due to the low tidal range, extensive alluvial and coastal lowlands, high subsidence rates, and high sedimentation rates. Coastal swamps and marshes cover most of the region. Half the wetlands that would be lost in the southeast, with a 1-meter rise in sea level and standard protection of developed areas, are in Louisiana (Table 2).

Luling-Pelican, Louisiana. This strip of four sites forms a transect from the western suburbs of New Orleans (including the airport) to the Gulf of Mexico (Figure 27). The area is now losing wetlands rapidly due to subsidence and human disturbance. The simulations represent an approximate response to sea level rise, but do not represent the complex interactions of changing river courses, floodwater diversions, variable sediment supplies, and salinity controls that affect the coastal ecosystems. These are better treated by region- and site-specific models such as that by Costanza et al. (1987). The tenuous position of the saltmarshes is shown by the baseline simulation in which most of the present saltmarshes are lost by the year 2100 (Figure 27B). The half-meter simulation (Figure 27C) is almost identical to the baseline, which coincides with the flat regional response for that range of sea levels (Figure 26).

West Coast

California (Figure 28) is characterized by rugged coastlines with low-lying areas. Most wetlands are in San Francisco Bay, where the high tidal range and high sedimentation rates created extensive wetlands prior to their destruction by dredge fill and by diking for salt ponds. At present, high subsidence rates and erosion rates are contributing to the decline of the remaining marshes. Heavy development has left little potential for the spread of wetlands onto adjacent lowlands. However, the model shows an unexpected spread of wetlands (Table 2). This appears to be due to errors in digitizing the elevations; also, salt pannes are not modeled in the current version. Until the data are checked thoroughly, the significant increase in wetlands under all scenarios should be viewed with suspicion.

Benicia, California. The remaining wetlands, now only a fraction of their original extent, are adjacent to developed areas and diked lowlands and salt ponds; they are lost with even a half-meter rise in sea level (Figure 29). If lowland areas were not protected, the marshes would migrate inland with sea level rise.

The Pacific Northwest (Figure 30), like California, is characterized by rugged, high-energy coasts and few low-lying areas. Where the topography is suitable for marsh formation, as in Yaquina Bay, Oregon, high tidal ranges would help to perpetuate those marshes despite a half-meter sea level rise.

Although the sample size is small and the data should be checked further, this initial study estimates the area of current vegetated wetland of the West Coast to be 64 mi^2. As shown in Figure 31 (which illustrates the total protection scenario and is not subject to elevational errors), aggregated wetlands exhibit a rather flat response to sea level rise.

Northeast

This diverse region (Figure 32) is similar to the West Coast with its high tidal ranges and rocky coasts, but includes easily eroded Cape Cod. This initial study estimates the area of vegetated wetlands to be 600 mi^2. The subsample of four sites is too small to define the region well; however, a pattern does emerge. Swamps developed on poorly drained glacial tills occur at elevations above those that could be inundated by sea level rise

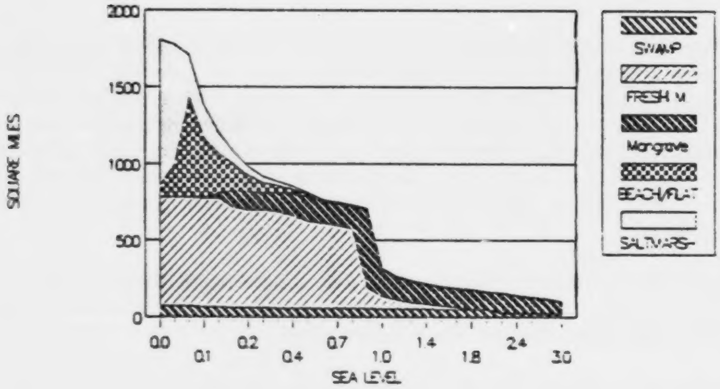


Figure 24. Changing areas of northern Gulf Coast coastal wetlands (excluding Louisiana) with global warming and sea level rise, and with existing developed areas protected.

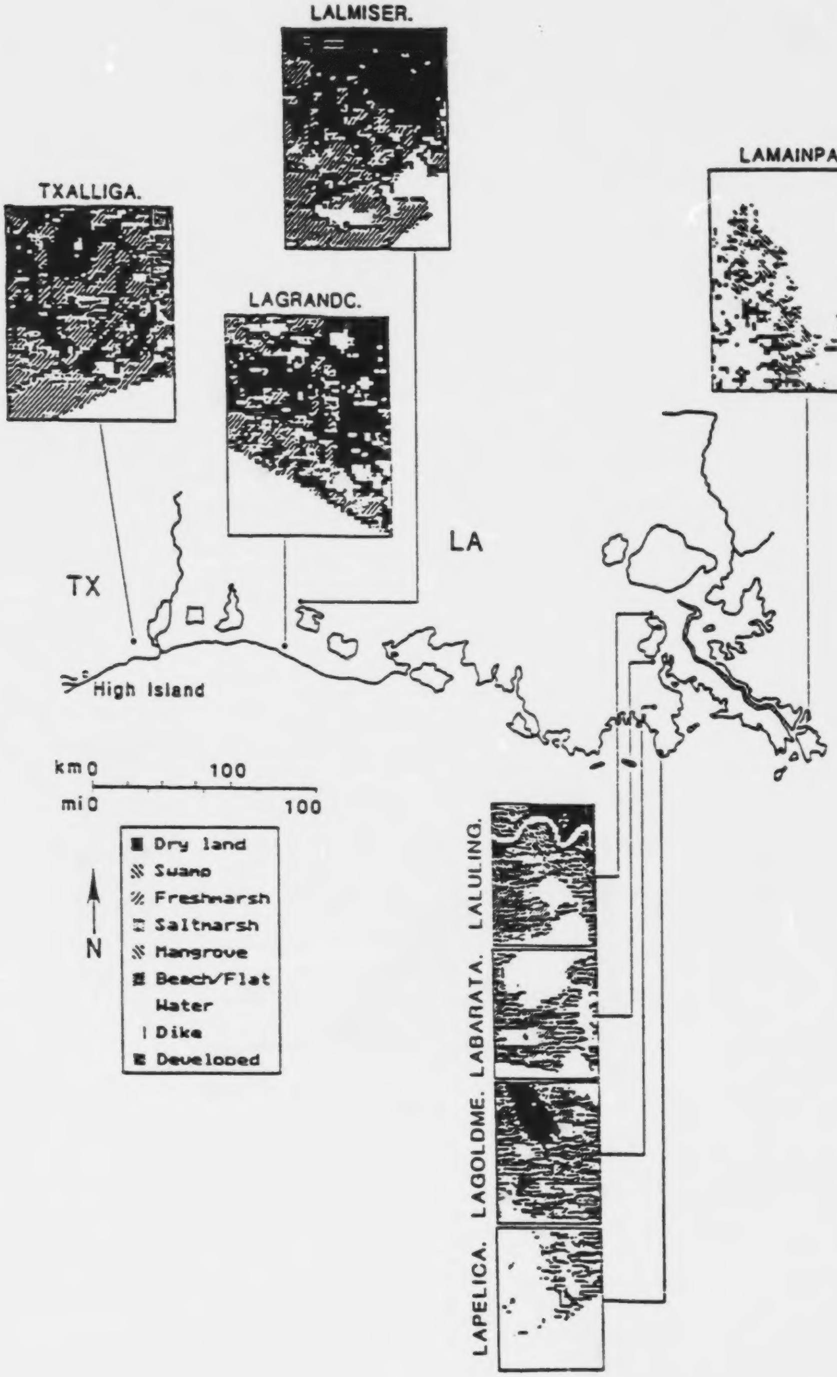

LALMISER.
TXALLIGA.
LAGRANDC.
LAMAINPA.
LA
TX
High Island
km 0 100
mi 0 100
Dry land
Swamp
Freshmarsh
Saltmarsh
Mangrove
Beach/Flat
Water
Dike
Developed
N
LALULING.
LABARATA.
LAGOLDME.
LAPELICA.

Figure 25. Index map of Mississippi delta and Louisiana-Texas chenier plain sites.

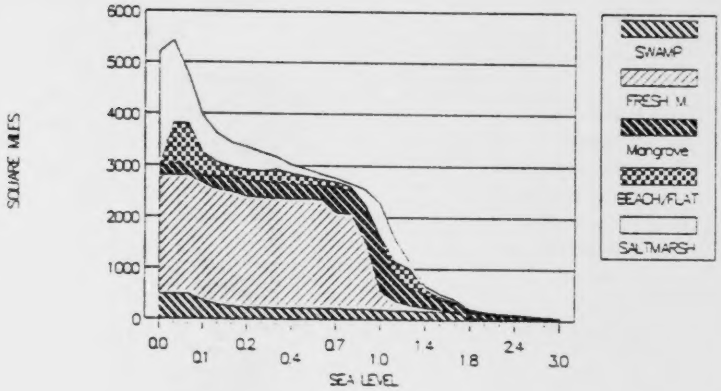


Figure 26. Changing areas of Louisiana coastal wetlands with global warming and sea level rise, and with existing developed areas protected.

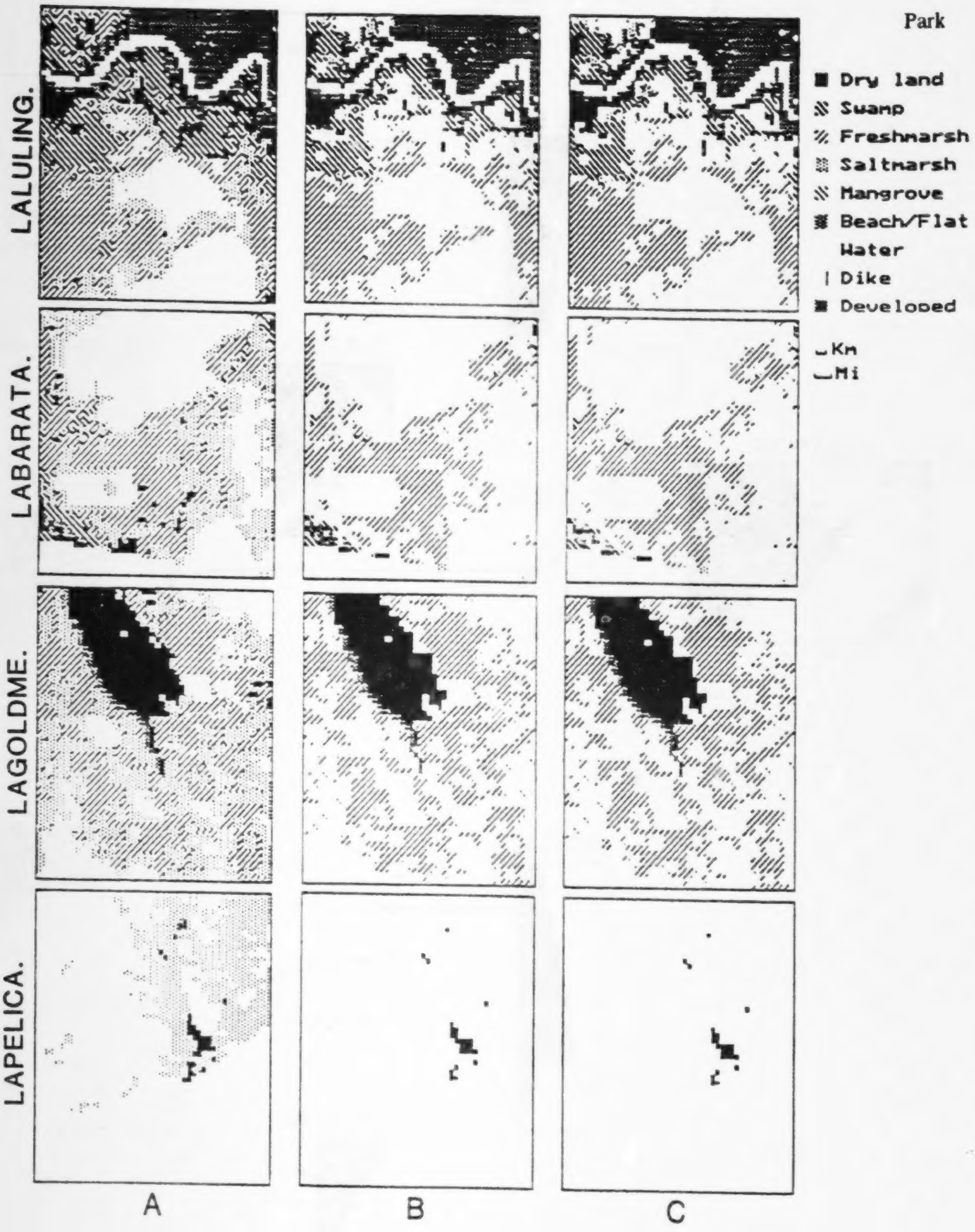

LALULING.
LABARATA.
LAGOLDME.
LAPELICA.
Park
Dry land
Swamp
Freshmarsh
Saltmarsh
Mangrove
Beach/Flat
Water
Dike
Developed
Km
Mi
A
B
C

Figure 27. Sites south of New Orleans, Louisiana, showing initial conditions (A) and predicted conditions for the year 2100 with 0.14-cm (B), 0.5-m (C), and 1.0-m (D) sea level stands.

Park

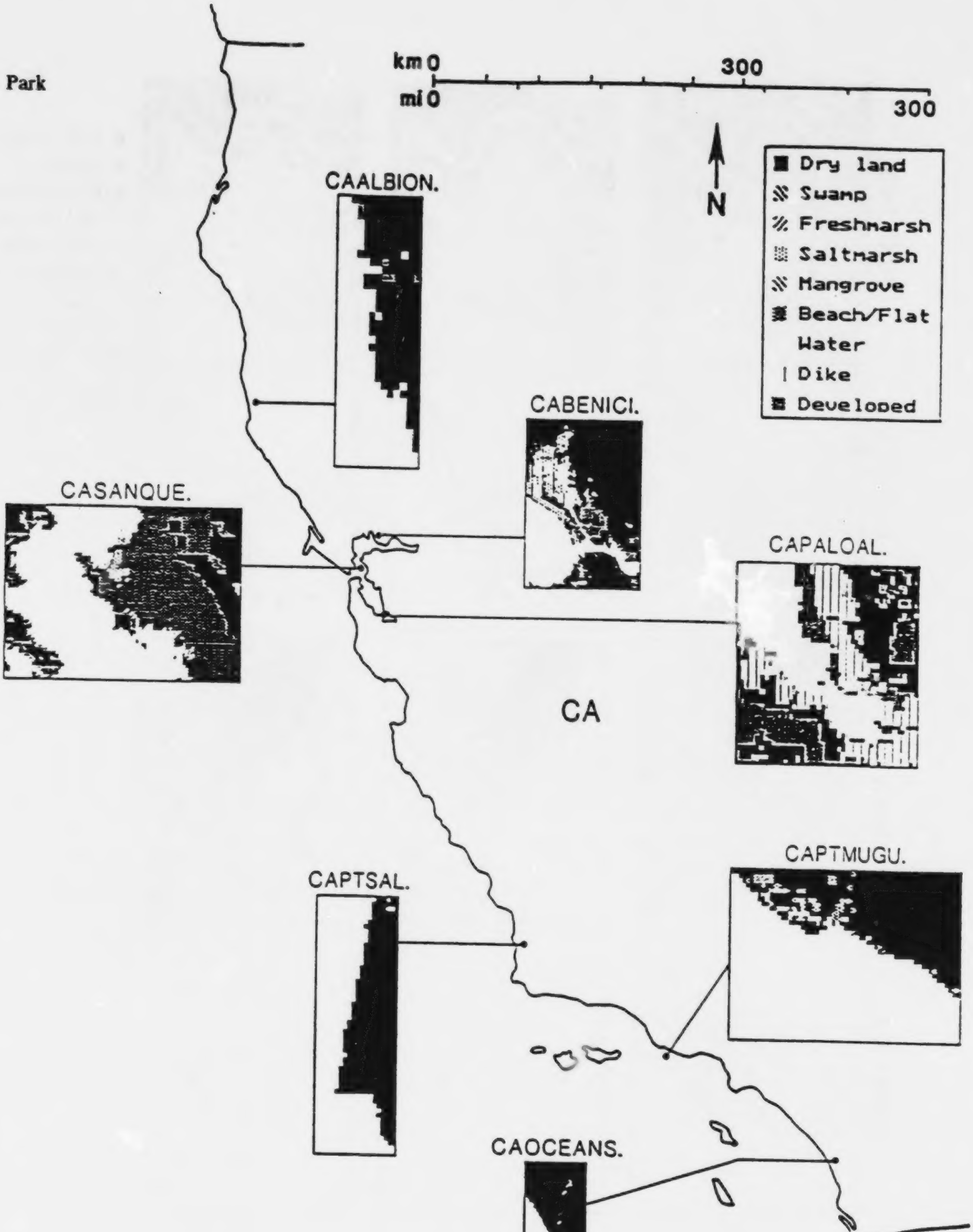
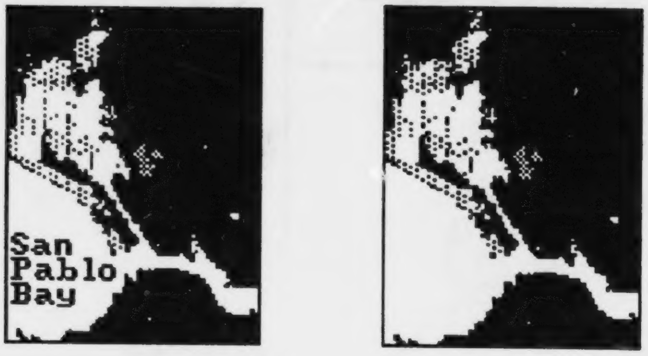

km 0
300
mi 0
300
N
■ Dry land
▨ Swamp
▨ Freshmarsh
▨ Saltmarsh
▨ Mangrove
▨ Beach/Flat
Water
| Dike
▨ Developed
CAALBION.
CABENICI.
CASANQUE.
CAPALOAL.
CA
CAPTSAL.
CAPTMUGU.
CAOCEANS.

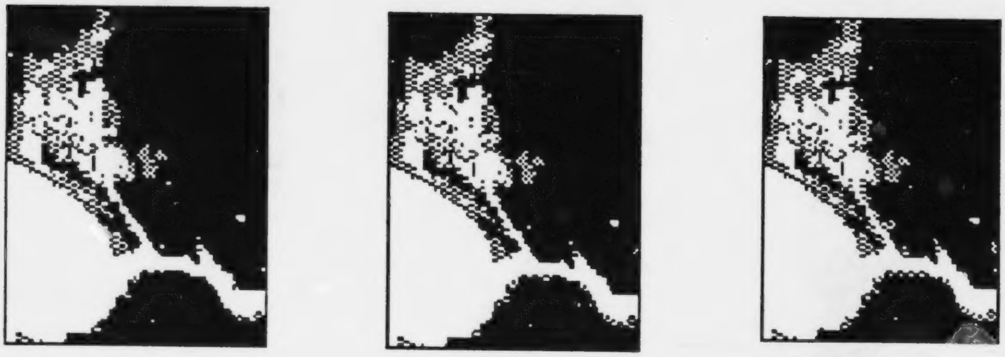
Figure 28. Index map of California sites.



A Present conditions

B Protected, 14 cm

C Protected, 0.5 m



D Protected, 1.0 m

E Protected, 2.0 m

⌴Km ⌴Mi

F Protected, 3.0 m

■ Dry land ▩ Developed ▧ Swamp

▨ Freshmarsh ░ Saltmarsh ▧ Mangrove

▩ Beach/Flat ☐ Water | Dike

Figure 29. Maps of the Benicia, California, site showing present conditions and predicted conditions for the year 2100, with protection of residential and commercial developments and with sea levels as indicated. Note the extensive tidal flats at higher sea levels.

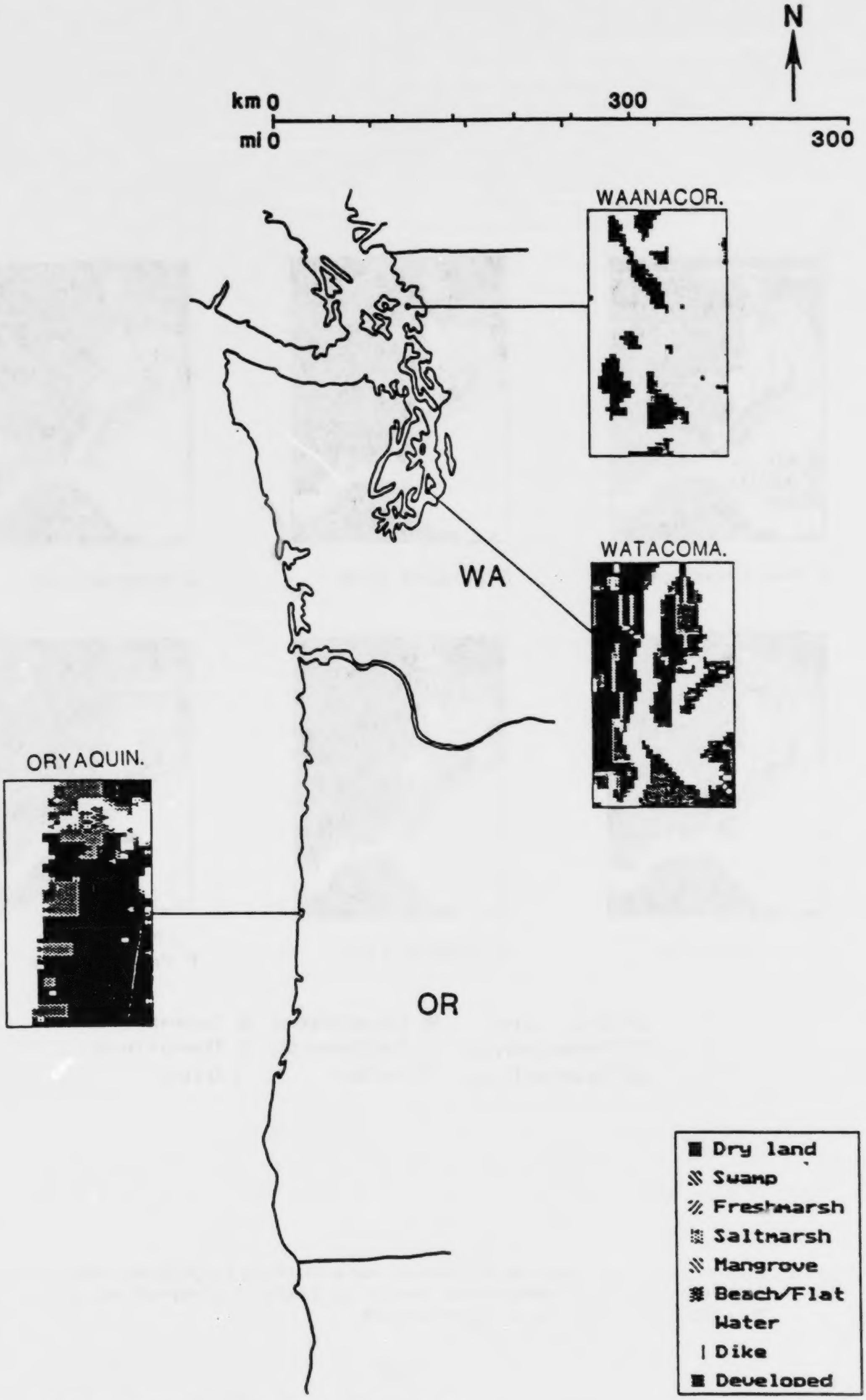

N
km 0
300
mi 0
300
WAANACOR.
WATACOMA.
WA
ORYAQUIN.
OR
Dry land
Swamp
Freshmarsh
Saltmarsh
Mangrove
Beach/Flat
Water
Dike
Developed

Figure 30. Index map of Pacific Northwest sites.

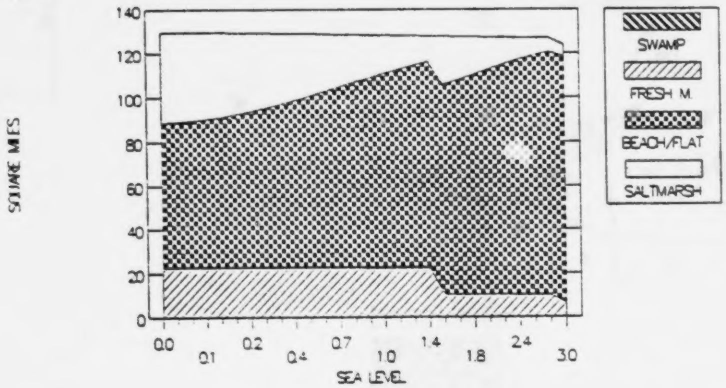


Figure 31. Changing areas of West Coast coastal wetlands with global warming and sea level rise, and with all dry land protected.

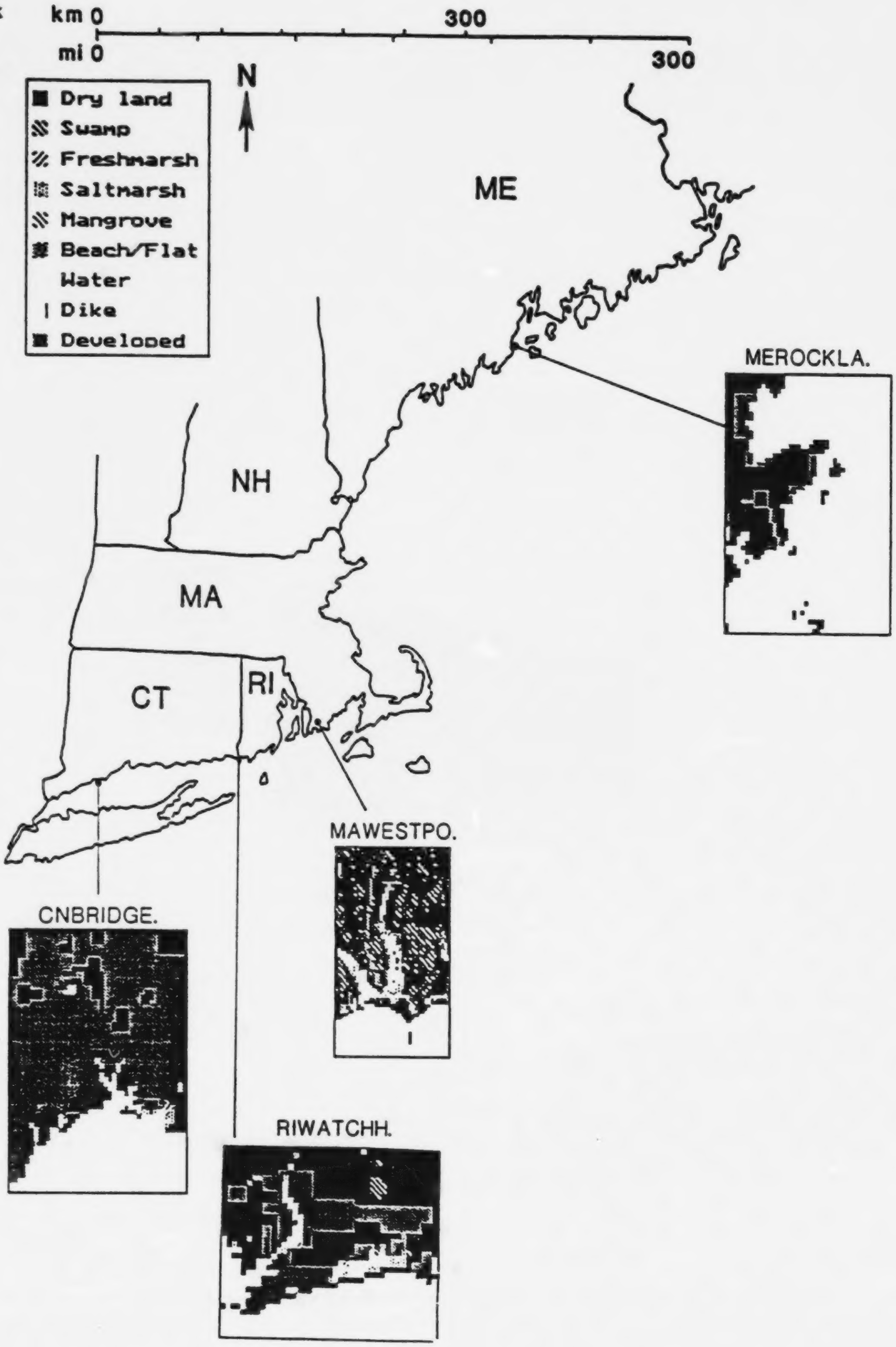
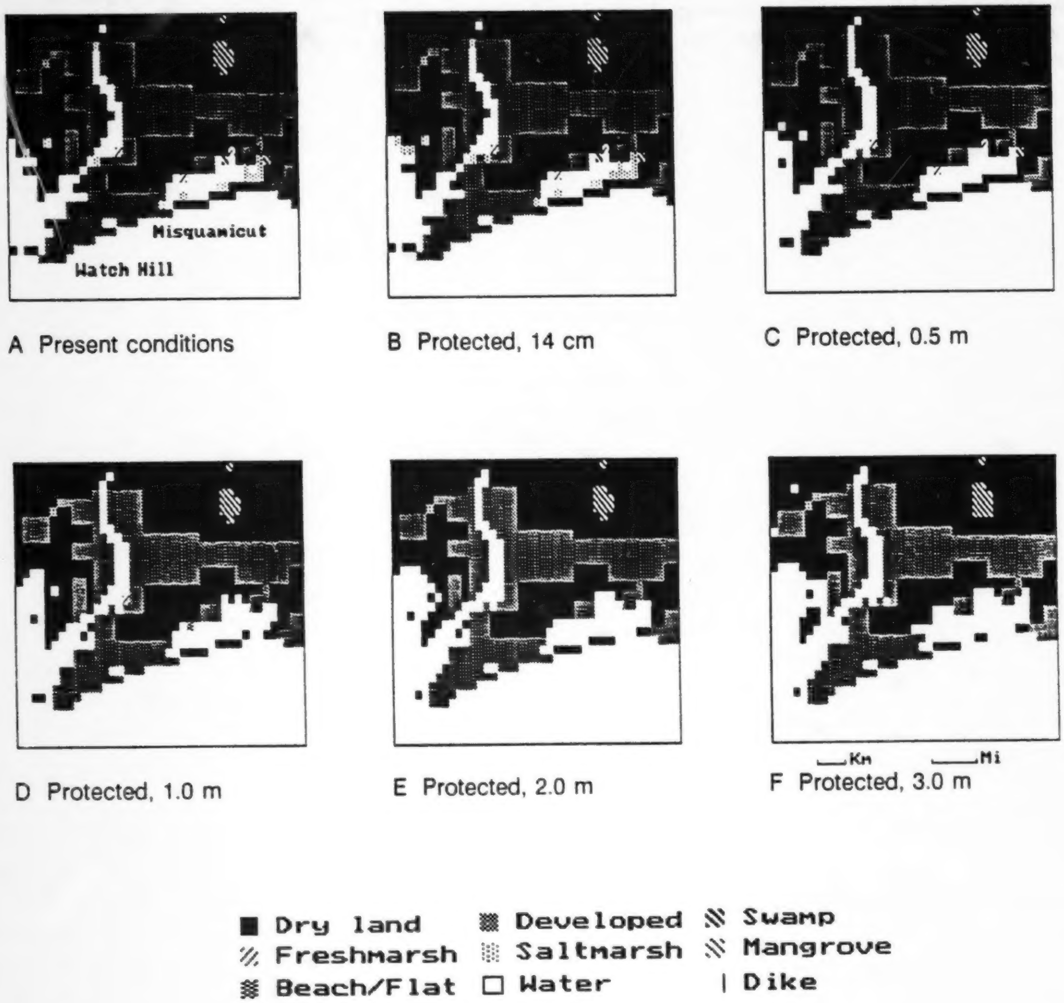

km 0
300
mi 0
300
N
■ Dry land
▨ Swamp
▨ Freshmarsh
▨ Saltmarsh
▨ Mangrove
▨ Beach/Flat
Water
| Dike
■ Developed
ME
NH
MA
CT
RI
MEROCKLA.
MAWESTPO.
CNBRIDGE.
RIWATCHH.

Figure 32. Index map of New England sites.

in the next century and therefore persist. Some coastlines, such as parts of the Maine coast, have no marshes at present and will not develop marshes due to the rocky substrate. Other areas have marshes protected by baymouth bars and spits; these marshes will not be affected adversely by lower stands of sea level.

Watch Hill, Rhode Island. This site includes the historic resort town of that name, with a long, narrow spit maintained by longshore drift to the west. It also includes Misquamicut Beach and adjacent marsh (Figure 33). The marsh will gradually disappear with higher sea level and eventually Misquamicut Beach will be breached, according to the simulations.


Misquamicut
Watch Hill
Km
Mi
■ Dry land
▩ Developed
▧ Swamp
▨ Freshmarsh
▒ Saltmarsh
▧ Mangrove
▩ Beach/Flat
☐ Water
| Dike

A Present conditions

B Protected, 14 cm

C Protected, 0.5 m

D Protected, 1.0 m

E Protected, 2.0 m

F Protected, 3.0 m

Figure 33. Maps of the Watch Hill, Rhode Island, site showing initial conditions (A) and predicted conditions for the year 2100, with protection of residential and commercial developments and with sea levels as indicated. Note the breaching of Misquamicut Beach and loss of marshes.

CHAPTER 4

SUMMARY

Projections of coastal wetland and lowland changes are made using remotely sensed cover-class data, lowland elevations digitized from topographic maps, and a simulation model based on simple geometric relationships of inundation and subsidiary influences of spatially varying exposure and erosion relationships. Approximately 9% of the coast of the contiguous United States was sampled in this phase of the study. Forty-six sites were chosen using an unbiased, systematic sample of coastal topographic maps; several additional sites were chosen for purposes of model verification.

Examination of eight representative sites provides insights into local responses of wetlands to accelerated sea level rise. Some sites, such as Sea Island, Georgia, are well buffered for sea levels up to 1 meter, due to high tidal ranges and high sedimentation and accretion rates. Other sites, especially in the Gulf of Mexico, are quite vulnerable to small changes in sea level; Long Beach, Mississippi, could be completely inundated by less than a 1-meter rise. Although the model is perhaps too simple for representing complex deltaic dynamics, it projects a continuation of current trends for the Louisiana coast south of New Orleans, with the entire undiked area shown to be at risk without any acceleration in sea level rise.

Composite responses were obtained by summing cover-class areas for each simulation time step for sites comprising a regional sample, and by transforming the values into regional estimates. The results are presented in Table 2 and as area graphs showing the patterns of changes in wetland areas with an exponential increase in sea level up to 3 meters. Regional responses are as follows:

- The mid-Atlantic Coast, with 746 mi^2 of diverse wetlands and moderate tidal ranges, would probably exhibit a gradual decline in vegetated wetlands and an increase in tidal flats; with standard protection of all currently developed lowlands, 27% of marshes and swamps would be lost with a 0.5-m rise by the year 2100, 46% with a 1-m rise, 58% with a 2-m rise, and 77% with a 3-m rise.

- The South Atlantic Coast, with 3,813 mi^2 of vegetated wetlands, is predicted to exhibit a gradual decline in vegetated wetlands by the year 2100, with mangrove swamps replacing saltmarshes as the dominant saltwater vegetated wetland at the more southerly sites; with standard protection, 38% of the fresh- and saltwater wetlands would be lost with a 0.5-m rise, 44% with a 1-m rise, 48% with a 2-m rise, and 58% with a 3-m rise.

- The southern and western coasts of Florida, with 1,869 mi^2 of vegetated wetlands, have large expanses of low-lying, undeveloped areas suitable for wetlands to migrate onto; therefore, vegetated wetlands would not decrease greatly in area by 2100 unless extensive dikes were constructed. With standard protection, only 5% of existing vegetated wetlands would be lost with a 0.5-m rise, 8% with a 1-m rise, and 9% with a 2-m rise; however, 36% would be lost with a 3-m rise. As the entire region becomes subtropical, mangrove swamps would spread northward and saltmarshes would gradually disappear.

- The northern Gulf Coast, excluding Louisiana, is estimated to have 1,218 mi^2 of vegetated wetlands; with its low tidal ranges and general lack of suitable lowlands for wetlands to migrate onto, saltmarshes would be lost with low sea-level rises by 2100. With standard protection, 33% of the vegetated wetlands would be lost with a 0.5-m rise, 77% with a 1-m rise, 82% with a 2-m rise, and 89% with a 3-m rise. Mangroves would take the place of saltmarshes as the climate moderates.

- Louisiana is estimated to have had 4,835 mi^2 of vegetated wetlands at the time the satellite imagery was obtained; these wetlands are being lost at an alarming rate without accelerated sea-level rise. With standard protection, this study estimates that by 2100, 47% of the vegetated wetlands would be lost with a 0.14-m rise in eustatic sea level (the historic rise continued), 49% with a 0.5-m rise, 57% with a 1-m rise, 97% with a 2-m rise, and 99% with a 3-m rise.

The sample size is too small in this initial study to reach conclusions about the West and Northeast Coasts, but preliminary results suggest that wetlands would be lost gradually due to the ameliorating effect of high tidal ranges.

These regional tabulations were summed to obtain estimates and area graphs for the entire coast of the contiguous United States, which has approximately 14,000 mi^2 of coastal wetlands (including 13,145 mi^2 of vegetated wetlands) at the present time. With protection of all existing residential and commercial developments, by the year 2100 saltmarshes and freshwater swamps would gradually decline in area, mangrove swamps would gradually increase, and freshwater marshes would gradually decline until a sea level of 0.8 m is reached. Freshwater marshes would then disappear rapidly (reflecting a pattern seen in both the Gulf and mid-Atlantic Coasts); 35% of vegetated wetlands would be lost with a 0.5-m rise, 49% with a 1-m rise, 56% with a 2-m rise, and 68% (almost 9,000 mi^2) with a 3-m rise. If all coastal lowlands not already protected by dikes were allowed to be inundated by a 3-m rise, a more gradual loss of saltmarshes would occur compared to the standard protection scenarios; 30% of vegetated wetlands would be lost with a 0.5-m rise, 46% with a 1-m rise, 52% with a 2-m rise, and 65% with a 3-m rise. Conversely, total protection of all dry land would result in an accelerated decline in saltmarshes and no increase in areas of mangrove swamps; 50% of vegetated wetlands would be lost with a 0.5-m rise, 66% with a 1-m rise, 78% with a 2-m rise, and 83% with a 3-m rise.

Alternatively, we could consider the sea level rises of a half meter and 2 meters as being reasonable bounds on a probable 1-meter rise. Therefore, with no protection of dry land other than existing dikes, 3,900 to 6,900 mi^2 of vegetated wetlands could be lost by the year 2100. With existing residential and commercial developments protected, 4,300 to 7,400 mi^2 of vegetated wetlands could be lost; with all dry land protected, 6,500 to 10,200 mi^2 of vegetated wetlands could be lost.

Wetlands provide important habitat for many fish and wildlife species, including rare and endangered birds on all three coasts, and over half the commercially important coastal fish species of the Southeast. Wetlands also remove pollutants and protect inland areas from floods, storms, and high tides. Therefore, policy decisions should be made to protect these valuable natural resources from the consequences of global warming and sea level rise.

REFERENCES

Armentano, T.V., R.A. Park, and C.L. Cloonan. 1988. Impacts on wetlands throughout the United States. In Titus, James G. (ed.), Impact of Sea Level Rise on Coastal Wetlands in the United States. Washington: U.S. Environmental Protection Agency, pp. 87-149.

Bahr, L.M., Jr., R. Costanza, J.W. Day, Jr., S.E. Bayley, C. Neill, S.G. Leibowitz, and J. Fruci. 1983. Ecological Characterization of the Mississippi Deltaic Plain Region: A Narrative with Management Recommendations. FWS/OBS-82/69, Slidell, Louisiana: Fish and Wildlife Service, 189 pp.

Barth, M.C., and J.G. Titus. 1984. Greenhouse Effect and Sea Level Rise. New York: Van Nostrand Reinhold.

Bird, E.C.F. 1986. Mangroves and intertidal morphology in Westernport Bay, Victoria, Australia. Marine Geology, 69:251-271.

Browder, J.A., H.A. Bartley, and K.S. Davis. 1985. A probabilistic model of the relationship between marshland-water interface and marsh disintegration. Ecological Modelling 29:245-260.

Bruun, Per. 1962. Sea Level Rise as a Cause of Shore Erosion. Journal of the Waterways and Harbors Division, Proceedings of the American Society of Civil Engineers, 88(WW1):117-130.

Bruun, Per. 1986. Worldwide Impacts of Sea Level Rise on Shorelines. In Effects of Changes in Stratospheric Ozone and Global Climate, Vol. 4: Sea Level Rise, edited by James G. Titus, 99-128. Washington, DC:U.S. Environmental Protection Agency.

Costanza, R., C. Neill, S.G. Leibowitz, J.R. Fruci, L.M. Bahr, Jr., and J.W. Day, Jr. 1983. Ecological Models of the Mississippi Deltaic Plain Region: Data Collection and Presentation. U.S. Fish and Wildlife Service, Division of Biological Services, Washington, D.C. FWS/OBS-82/68, 342 pp.

Costanza, R., F.H. Sklar, M.L. White, J.W. Day, Jr. 1987. A dynamic spatial simulation model of land loss and marsh succession in coastal Louisiana In: Wetland Modelling, W.J. Mitsch, M. Straškraba, and S.E. Jørgensen (eds.), Elsevier, Amsterdam.

Dasarathy, B.V. 1974. HINDU: Histogram Inspired Neighborhood Discerning Unsupervised Pattern Recognition System. NASA/Computer Sciences Corp., Huntsville, Alabama, 43 pp.

Davis, R.A. 1985. Coastal Sedimentary Environments. New York: Springer-Verlag.

Day, J.W., Jr. W.G. Smith, P.R. Wagner, and W.C. Stowe. 1973. Community Structure and Carbon Budget of a Salt Marsh and Shallow Bay Estuarine System in Louisiana. Center for Wetland Resources, Louisiana State University, Baton Rouge. Publ. No. LSU-SG-72-04.

Dyer, K.R. 1986. Coastal and Estuarine Sediment Dynamics. Chichester, U.K.: John Wiley & Sons, 342 pp.

Estes, J.A., and G.A. Thorley. 1983. Manual of Remote Sensing, Vol. II: Interpretations and Applications. Second Edition. American Society of Photogrammetry.

Gosselink, J.G. 1984. The Ecology of Delta Marshes of Coastal Louisiana: A Community Profile. FWS/OBS-84/09, Washington, DC: U.S. Fish and Wildlife Service, 134 pp.

Hall, S.L., W.R. Wilder, and F.M. Fisher. 1986. An analysis of shoreline erosion along the northern coast of East Galveston Bay, Texas. Journal of Coastal Research 2:173-179.

Kana, T.W., B.J. Baca, and M.L. Williams. 1988a. Charleston case study. In: J. G. Titus (ed.), Greenhouse Effect, Sea Level Rise and Coastal Wetlands. EPA-230-05-86-013, U.S. Environmental Protection Agency, Washington, pp. 37-59.

Kana, T.W., W.C. Eiser, B.J. Baca, and M.L. Williams. 1988b. New Jersey case study. In: J. G. Titus (ed.), Greenhouse Effect, Sea Level Rise and Coastal Wetlands. EPA-230-05-86-013, U.S. Environmental Protection Agency, Washington, pp. 61-86.

Leatherman, S.P. and R.E. Zaremba. 1986. Dynamics of a northern barrier beach: Nauset Spit, Cape Cod, Massachusetts. Geological Society of America Bulletin 97:116-124.

Lefor, M.M., W.C. Kennard, and D.L. Civco. 1987. Relationships of salt-marsh plant distributions to tidal levels in Connecticut, USA. Environmental Management 11:61-68.

Letzsch, W.S. and R.W. Frey. 1980. Deposition and Erosion in a Holocene Salt Marsh, Sapelo Island, Georgia. Journal of Sedimentary Petrology, 50(2):529-542.

Lugo, A.E., and M.M. Brinson. 1978. Calculations of the value of salt water wetlands. In Wetland Functions and Values: The State of Our Understanding, pp. 120-130, American Water Resources Association.

Mausel, P.W. 1985. Remote Sensing: Introduction to Computer Assisted Techniques. ISURSL Information Note 09031985. Indiana State University Remote Sensing Lab, Terre Haute, pp. 72-79.

Montague, C.L., A.V. Zale, and H.F. Percival. 1987. Ecological effects of coastal marsh impoundments: a review. Environmental Management, vol. 11, pp. 743-756.

Park, R.A., T.V. Armentano, and C.L. Cloonan. 1986a. Predicting the impact of sea level rise on coastal systems. In Supplementary Proceedings for the 1986 Eastern Simulation Conference, Norfolk, Virginia, pp. 149-153.

Park, R.A., T.V. Armentano, C.L. Cloonan. 1986b. Predicting the effects of sea level rise on coastal wetlands. In James G. Titus (ed.), Effects of Changes in Stratospheric Ozone and Global Climate, Vol. 4: Sea Level Rise, pp. 129-152, Washington: U.S. Environmental Protection Agency.

Peltier, W.R. 1988. Global sea level and earth rotation. Science, vol. 240, pp. 895-901.

Pope, R.M., and J.G. Gosselink. 1973. A tool for use in making land management decisions involving tidal marshland. Coastal Zone Management Journal. 1:65-74.

Ryszkowski, Lech. 1984. Primary production in agroecosystems. Options Mediterraneennes. Mediterranean Agronomic Institute of Saragossa, Spain, 84(1):77-94.

Sherrod, C.L., and C. McMillan. 1985. The distributional history and ecology of mangrove vegetation along the northern Gulf of Mexico. Contributions in Marine Science, 28:129-140.

Sklar, R. Costanza, and J. W. Day, Jr. 1985. Dynamic spatial simulation modeling of coastal wetland habitat succession. Ecological Modelling 29:261-281.

Swanson, R.L., and C.I. Thurlow. 1973. Recent subsidence rates along the Texas and Louisiana coasts as determined from tide measurements. Journal Geophysical Research 78:2665-2671.

Teal, J.M. 1962. Energy flow in the salt marsh ecosystem of Georgia. Ecology 43:614-624.

Teal, J.M., and M. Teal. 1969. Life and Death of the Salt Marsh. New York: Audobon-Ballantine.

Thomas, R. 1986. Future sea level rise and its early detection by satellite remote sensing. In James G. Titus (ed.), Effects of Changes in Stratospheric Ozone and Global Climate, Vol. 4: Sea Level Rise, pp. 19-36, Washington: U.S. Environmental Protection Agency.

Thurman, H.V. 1983. Essentials of Oceanography. Columbus, Ohio: Charles E. Merrill.

Titus, J.G. ed. 1986. Effects of Changes in Stratospheric Ozone and Global Climate, 4 vols. Washington: U.S. Environmental Protection Agency.

Titus, J.G. ed. 1988. Greenhouse Effect, Sea Level Rise and Coastal Wetlands. EPA-230-05-86-013, Washington: U.S. Environmental Protection Agency.

Titus, J.G., and S.R. Seidel. 1986. Overview of the effects of changing the atmosphere. In James G. Titus (ed.), Effects of Changes in Stratospheric Ozone and Global Climate, Vol. 1: Overview, pp. 3-19, Washington: U.S. Environmental Protection Agency.

Villach. 1985. International assessment of the role of carbon dioxide and of other greenhouse gases in climate variations and associated impacts. Conference Statement. Geneva: United Nations Environment Program.

Watkins, J.S., M.L. Bottino, and M. Morisawa. 1975. Our Geological Environment. Philadelphia: W. B. Saunders.

Wiegert, R.G., R.R. Christian, J.L. Gallagher, J.R. Hall, R.D.H. Jones, and R.L. Wetzel. 1975. A preliminary ecosystem model of a coastal Georgia Spartina marsh. In Estuarine Research, Vol. 1, edited by L. E. Cronin, pp. 583-601. New York: Academic Press.

NATIONAL ASSESSMENT OF BEACH NOURISHMENT REQUIREMENTS ASSOCIATED WITH ACCELERATED SEA LEVEL RISE

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Contract No. 68-01-72-89

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CHAPTER 1

INTRODUCTION[1]

A significant portion of the United States population lives within the coastal zone, with many buildings and facilities located at elevations less than 3 meters (10 feet) above sea level. These structures are presently subject to damage during storms, and this hazard has grown increasingly serious as sea levels have risen during the twentieth century. Greenhouse-induced warming is expected to raise water levels at historically unprecedented rates, resulting in increased beach erosion and flooding.

Despite these potential hazards, the coastal population is burgeoning. In fact, development in the coastal zone is proceeding at rates that more than double inland construction. Hundreds of thousands of beachfront structures (exquisite single-family houses, high-rise condominiums, and elegant hotels) have been built within a few hundred feet of an eroding ocean shore. Beachfront property is some of the most valuable real estate in the country, exceeding $20,000 per linear foot of shoreline along the U.S. mid-Atlantic coast.

The present dilemma and developing disaster have resulted from the tremendous investment in coastal property at a time when most sandy beaches nationwide are eroding. Best estimates are that 90 percent of the U.S. sandy beaches are presently experiencing beach erosion (Leatherman, 1986). Accelerated sea-level rise will increase erosion rates and associated problems.

Public attention is yet to be critically focused on the beach erosion problem. The present (1988) drought and heat wave have brought about a dramatic awakening and interest of citizens in the greenhouse effect and climate change. Hopefully, a coastal disaster along an urbanized beach will not be necessary to promote public awareness of the sea level rise phenomenon and its attendant impacts.

Sea level is a primary control on shore position, which, in human terms, translates to beach erosion when water levels are rising. While weather is subject to large-scale variations and hence climate change trends are difficult to measure, rising sea levels are relatively easy to discern and can be thought of as the dipstick of climate change, reflecting the integration of many earth surface processes.

There are three general responses to accelerated sea level rise: retreat from the shore, armor the coast, or nourish the beach. Beach nourishment is the focus of this report, wherein sand is artificially placed on the beach. Other tactics for combatting the sea level rise/coastal erosion problem are discussed elsewhere in this volume. The proper shore protection response is site-specific on a community or coastal sector basis due to large differences in environmental and socioeconomic factors. The abandonment alternative is not realistic for urbanized beaches. For less developed areas along eroding shorelines, planning decisions are less clear cut. Therefore, the costs and benefits of stabilization vs. retreat must be carefully considered as the cost in either case is likely to be quite high (National Research Council, 1987).

The principal approach today of protecting coastal property and maintaining recreational beaches is beach nourishment. Engineering structures, such as groins and seawalls, have often been shown to cause detrimental effects on adjacent beaches. Also, their construction and maintenance costs are quite high. Therefore, coastal communities have come to rely upon a "soft" engineering solution -- beach nourishment, since it is environmentally sound, aesthetically pleasing, and up-to-this-time, economically feasible. However, the projected accelerated sea level rise will cause more rapid rates of beach loss and could make even this alternative too costly for many resort areas along the United States coastline.

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[1] Although the information in this report has been funded wholly or partly by the U.S. Environmental Protection Agency under Contract No. 68-01-72-89, it does not necessarily reflect the Agency's views, and no official endorsement should be inferred from it.

OBJECTIVE

The overall objective of this research is to estimate the cost to nourish all the major recreational oceanic beaches in the U.S., given various sea level rise scenarios. It is clear that developed coastal resort residents would prefer not to move back and abandon the coast and will attempt to stabilize the shore through beach fill projects. The approach is to place enough sand on the beach to maintain stable (nonretreating) conditions with rising sea levels. The quantity of sand required "to hold the line" is evaluated under various sea level rise scenarios (rise/year combinations) at foot intervals up to a 10-foot rise situation by the year 2100.

REPORT OUTLINE

This Introduction is followed by a general Methodology section. The beach nourishment analysis were undertaken at the community level, from which state and national totals were determined. Delray Beach, Florida, was selected as a case study to illustrate the type of analysis conducted for each area. Finally, the national results are presented. Of the approximately 7,000 miles of sandy shoreline in the U.S., 1,920 miles of beaches were evaluated in this study. These areas are considered to be the principal recreational beaches in the country.

CHAPTER 2

METHODOLOGY

STUDY SITES

This report focuses on the twenty-one coastal states in the United States. Alaska is excluded because of its undeveloped nature. Some states have only one to a few coastal resort areas (e.g., Ocean City in Maryland), while others, particularly Florida and New Jersey, are known for their many recreational beaches. The major recreational beaches in each state are examined; state averages for nourishment needs are then tabulated from the site-specific calculations. Therefore, cost estimates of beach fills are made based on local (community or physiographic) conditions to produce statewide and national assessments.

DATA SOURCES

The last national assessment of shore erosion and associated planning implications was undertaken by the U.S. Army Corps of Engineers in 1971. Their national survey, based on District Corps office reports, indicated the prevalence of shore erosion. In addition, there are numerous site-specific reports and information available for various locales. These data were assembled and analyzed to extract information pertinent to the study. Corps District personnel and State Coastal Zone Management (CZM) officials were also queried for any up-to-date information and insights. Specifically, the basic information for analysis was largely obtained from the following sources: U.S.G.S. topographic maps for areal measurements and offshore contours, National Research Council (1987) report for sea level rise scenarios, supplemented by estimates from Hoffman et al (1986), baseline relative sea level rise rates for U.S. coast (Lyles et al., 1987), and CERC Inner-Continental Shelf Studies (ICONS) data sets on offshore sand resources.

COASTAL SEGMENTATION

The coast in each state is divided into three categories: (1) publicly owned, undeveloped; (2) privately owned, undeveloped, and (3) already developed. Roughly one-third of the U.S. coast falls into each of these categories. Publicly owned, undeveloped areas (e.g., state parks, national seashores, and NASA installations) will most likely never be developed, but some areas may be nourished. In general, these areas are not considered in the nourishment assessment, unless beach fill has already been undertaken and is likely to continue (e.g., Huntington Beach State Park, SC).

Most of the areas contained in the privately owned, undeveloped coastal area category are identified in the 1983 U.S. Congress COBRA legislation, and usually are excluded from receiving federal assistance in shoreline stabilization by law. However, these areas still have the potential to be developed, and are therefore included in the national assessment. Inclusion of these locales represents a worst case scenario in terms of the total amount of area needing nourishment.

Developed areas have already been urbanized or are already somewhat developed and are likely to be extensively developed in the future. Beaches that have been nourished in the past or have undergone full-scale urbanization are the best candidates for further restoration. Areas are delimited along the coast by jurisdictional (e.g., town, city) boundaries or natural demarcations (e.g., inlets) into geomorphic units.

CLOSURE DIMENSIONS

Offshore closure depth is specified for each area on the basis of Hallermeier's (1981) determinations for the U.S. coast. Hallermeier's (1981) approach relies upon statistical wave data, which is available for the entire U.S. coast, and his work represents the state-of-the-art in the field. Some may feel that the derived values for closure depth are too conservative in certain areas. In this case, a simple ratio of utilized and preferred values can be used to calculate higher sand volumes and costs.

The U.S. Geological Survey 7.5-minute quadrangles, supplemented by National Ocean Service nautical charts, were used to determine the horizontal distance offshore to closure depth for each coastal sector. This data source was selected since U.S.G.S. quadrangles (1:24,000 scale) are the most commonly utilized maps in the country, depicting both surficial (e.g., urban development and topography) features and offshore contours.

SEA LEVEL RISE SCENARIOS

A total of six sea level rise (SLR) scenarios are considered in this analysis, evaluated from 1 to 10 feet at 1-foot intervals but without the time exceeding year 2100. These scenarios are based on previous studies by the National Research Council (1987) and the U.S. Environmental Protection Agency (see Titus and Greene, this volume). The total component of rise can be calculated as follows: $T(t) = (0.0012 + M/1{,}000)t + tb^2$, where M is the local (isostatic) factor (in mm/yr) and b describes the concaval upward slope of the quadratic equation. Estimates of M from Lyles et al. (1987) can be obtained from Table 1 as determined by NRC (1987), and values of the coefficient b are listed in Table 2 for the six scenarios.

SAND VOLUME DETERMINATIONS

The direct approach of "raising the beach/nearshore profile" is utilized because of its straightforward application. The beach to offshore closure depth distance (d) represents the active profile dimension. For every increment (x) of sea level rise, the volume of sand required to "raise the profile" simply corresponds to xd per unit of shoreline length. This approach overcomes objections to the Bruun Rule formulation regarding on/offshore sand transport. Also, other methodologies require considerably more data (e.g., Trend Analysis necessitates knowledge of historical shoreline change and the Sediment Budget Model involves site-specific information on transport rates; Leatherman, 1985). In this analysis, longshore losses are shown separately in the tables so that the sand required to mitigate accelerated sea level rise, alone, is clearly stated.

As sea level rises, the land surface becomes relatively lower with respect to mean water level, resulting in increased frequency and more severe coastal flooding. For barrier islands, the decision will likely be made at some point to raise the barrier elevations to overcome or lessen the effects of this problem. It is assumed that after 1 foot of sea level rise, coastal communities will start raising the bayside areas of the island, which are less than 5 feet above mean sea level. Prior to this point, it can be argued that the cost and nuisance of such actions would dictate inaction, and people would tolerate the increased flooding. By the time a 4-foot rise in mean sea level is achieved, the entire barrier surface, including the dunes but excluding wetlands, will have been raised in concert with water levels to prevent storm overtopping. Therefore, the procedure involves calculation of the elevational distribution above and below the 5-foot (MSL) elevation to compute the area and hence volume of sand required with different scenarios of sea level rise. Some barrier islands and mainland areas had general elevations above the 15-foot contour line. No mitigating action was deemed necessary for these areas.

SAND RESOURCE AVAILABILITY

Once the quantities of sand required to maintain the recreational beaches for various SLR scenarios have been established, a determination of available sand resources available to match this projected need must be undertaken. The preferred borrow site areas are generally located offshore for most states. Backbarrier lagoons and bays have been utilized in the past for small quantities of material, but environmental objections and incompatibility of material because of size have precluded further use of such sources. Mining of mainland sand pits has been employed locally in some areas, but again the resources are limited and this type of activity is not permitted in most states.

Table 1. Relative Sea Level for the United States Coast, 1850-1986*

Location	Trend mm/yr	Trend ft/yr
Atlantic Coast		
Eastport, ME	2.7	.009
Bar Harbor, ME	2.7	.009
Portland, ME	2.2	.007
Seavey Is., ME	1.8	.006
Boston, MA	2.9	.010
Woods Hole, MA	2.7	.009
Newport, RI	2.7	.009
Providence, RI	1.8	.006
New London, CT	2.1	.007
Bridgeport, CT	2.1	.007
Montauk, NY	1.9	.006
Port Jefferson, NY	2.7	.009
Willets Pt., NY	2.4	.008
New Rochelle, NY	0.6	.002
New York, NY	2.7	.009
Sandy Hook, NJ	4.1	.014
Atlantic City, NJ	3.9	.013
Philadelphia, PA	2.6	.008
Lewes, DE	3.1	.010
Baltimore, MD	3.2	.010
Annapolis, MD	3.6	.012
Solomons Is., MD	3.3	.011
Washington, DC	3.2	.011
Kiptopeke, VA	3.1	.010
Hampton Roads, VA	4.3	.014
Portsmouth, VA	3.7	.012
Wilmington, NC	1.8	.006
Charleston, SC	3.4	.011
Ft. Pulaski, GA	3.0	.010
Fernandina, FL	1.9	.006
Mayport, FL	2.2	.007
Miami Beach, FL	2.3	.008
Key West, FL	2.2	.007

Location	Trend mm/yr	Trend ft/yr
Gulf Coast		
St. Petersburg, FL	2.3	.007
Cedar Key, FL	1.9	.006
Pensacola, FL	2.4	.008
Grand Isle, LA	10.5	.034
Eugene Island, LA	9.7	.032
Sabine Pass, TX	13.2	.043
Galveston, TX	6.4	.021
Galveston, TX	7.5	.024
Freeport, TX	14.0	.046
Rockport, TX	4.0	.013
Padre Island, TX	5.1	.017
Port Isabel, TX	3.1	.010
Pacific Coast		
San Diego, CA	2.1	.007
La Jolla, CA	2.0	.007
Newport, CA	1.9	.006
Los Angeles, CA	0.8	.003
Santa Monica, CA	1.8	.006
Port San Luis, CA	1.2	.004
San Francisco, CA	1.3	.004
Alameda, CA	1.0	.003
Crescent City, CA	-0.6	-.002
Astoria, OR	-0.3	-.001
Neah Bay, WA	-1.1	-.004
Seattle, WA	2.0	.006
Friday Harbor, WA	1.4	.004
Nawiliwili, HI	2.0	.006
Honolulu, HI	1.6	.005
Hilo, HI	3.6	.012

*Source: Lyles et al (1987)

Table 2. Value of Coefficient "b" for Six Scenarios Considered in This Study

Scenario*	Eustatic Component (by year 2100 in m)**	"b" Coefficient (m/yr^2)
I	0.5	.00002795
II	1.0	.00006642
III	1.5	.00010490
IV	2.0	.00011340
V	2.5	.00018180
VI	3.0	.00022030

* Source: Scenarios I, II, and III; NRC (1987)
Scenarios IV, V, and VI; EPA (1986)

**Projections do not exceed year 2100

Inlet sand shoals (termed "ebb tidal deltas") often contain large quantities of beach sand and are located in close proximity of important resort areas, particularly in the State of Florida. Future plans for dredging of these inlets and outer shoals for ship navigation should include a provision for sand placement on adjacent or specified beach areas, rather than dumping sand far offshore in deep water. Unfortunately, some inlet material is chemically polluted, particularly in the New York-New Jersey metropolitan areas, and there is also the concern of sand drawndown from adjacent beaches if extensive sand dredging and shoal removal are realized. In fact, the large ebb tidal delta off Ocean City, Maryland (8 million cubic yards of clean beach sand) probably will not be used in the forthcoming beach restoration project because of concerns of accelerated, post dredging erosion of adjacent beach areas. Therefore, only offshore borrow sites are considered in this analysis as ebb-tidal deltas are generally too small regarding sand volumes or clouded by political concerns (unless specifically recommended for usage by state authorities).

Offshore sources along the Atlantic Coast were delineated by a series of studies undertaken in the recent past by the U.S. Army Corps of Engineers Coastal Engineering Research Center (CERC). The Inter-Continental Shelf (ICONS) study involved all the states from New York to Florida, and these reports are used to obtain a good estimate of available sand reserves. This information is supplemented for the rest of the coast and updated by Corps District reports for specific areas. In addition, the U.S.G.S. and M.M.S. (Minerals Management Services) in association with various state geological surveys (e.g., Louisiana, Maryland, and Maine) have expanded and updated these inventories.

BEACH NOURISHMENT COSTS

Sand costs are estimated for the range of alternatives (e.g., various SLR scenarios evaluated at particular years when a certain sea level has been achieved). Values are based on current rates per cubic yard of material. A sand cost function was developed from past dredging experience and applied to each coastal sector. It is clear that as the less expensive, closer-to-shore sand supplies are exhausted, the costs will rise as a step-function (approximately $1.00 per cubic yard per mile farther offshore as booster pumps are added). The "base rates" vary regionally so that the actual costs are site-specific. This study gives us the ability to predict for the first time the nourishment requirements for various SLR scenarios and associated costs for individual resort areas, resulting in statewide and national estimates.

FLORIDA CASE STUDY[2]

The Delray Beach area along the Florida Atlantic coast was chosen as the case study to illustrate the type of analysis conducted in this report for coastal communities nationwide. The Delray Beach area in Florida is heavily developed and requires analysis at all levels addressed in this report; profile nourishment, backbarrier and oceanside elevation raising, sand volume requirements, offshore sediment supplies, and associated dredging costs. In addition, Delray Beach has been nourished in the past (1973, 1978, and 1984), and the state of Florida proposes to continue such projects in the future (Florida DNR, 1988).

Delray Beach is located in southeast Florida in rapidly growing Palm Beach County. It shares boundaries to the north and south with Boynton Beach and Boca Raton, respectively. The beach area functions as a barrier island as it is fronted by the Atlantic Ocean to the east and the Intracoastal Waterway to the west. The barrier is rather low-lying, with maximum elevations approximately 15 feet in the dune line. The barrier varies in width, but averages 1800 feet along its length. The beaches in this locale are composed of medium to coarse shelly sands and are underlain by similarly composed coquina rock (Florida DNR, 1988).

WAVE CLIMATE AND CLOSURE DEPTH SELECTION

Closure depth represents the seaward limit of significant sediment transport along a beach profile and is the offshore extent to which beach nourishment should occur. Nourishment of the beach profile to this distance is imperative for the success and longevity of beach replenishment projects; otherwise, wave action will rapidly rework the new sediment (which can appear as beach erosion to the casual observer), moving a portion of it offshore to attain profile equilibrium.

With these considerations in mind, a technique was developed (Hallermeier, 1981) to determine closure depths at various coastal locations in the U.S. based on local sand characteristics and summary statistics of annual wave climate (Table 3). The results of Hallermeier's work were used in this study to determine the appropriate offshore extent of proposed beach nourishment. When Hallermeier's (1981) predictions were not available for a particular study area, approximate closure depths were extrapolated from the closest given locations.

Hallermeier defined two offshore limits in his work, d_1 and d_i. The d_1 limit was used to estimate closure depths for this report, as it (d_1) represents the "maximum water depth for sand erosion and seaward transport by an extreme yearly wave condition, and corresponds to a seaward limit of appreciable seasonal profile change "(Hallermeier, 1981). The d_i value, on the other hand, corresponds to an offshore depth where "expected surface waves are likely to cause little sand transport" (Hallermeier, 1981). Therefore, to ensure inclusion in the active profile, sand introduced by beach nourishment should be added out to the offshore depth, d_1. Hallermeier's (1981) recommended applications for the seaward limit also suggest using dd_1 values as the offshore limit for beach nourishment projects. Although extreme storm events may move sand beyond the d_1 location, this report assumes that beach nourishment projects are based on average wave conditions.

The closure depth used for Delray Beach was 4.2 meters. This depth was determined from Hallermeier's (1981) work for Boca Raton, Florida (Table 3), the municipality immediately adjacent to southern Delray Beach. The area is subject to a mild wave climate (average height of 1.59 feet) and closure depths are relatively shallow and near the shore as a result.

After determining closure depths, United States Geological Survey (USGS) topographic maps (7.5-minute series) were used to estimate the distance from the shoreline to these depths. For example, the bathymetric points closest to 4.2 meters were located on the U.S.G.S. map for Delray Beach and measured as

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[2] This section was authored by Ms. Cary Gaunt, Laboratory for Coastal Research, University of Maryland.

Table 3. Selected Closure Depths for the United States Coastline (Hallermeier, 1981)

Site	Closure Depth (m)
Atlantic Coast	
Assateague, MD	5.40
Bull Island, SC	4.20
Tybee Lighthouse, GA	7.40
Boca Raton, FL	4.20
Lake Worth, FL	5.04
Atlantic City, NJ	7.04
Virginia Beach, VA	6.25
Nags Head, NC	7.95
Atlantic Beach, NC	5.65
Wrightsville Beach, NC	5.35
Holden Beach, NC	4.72
Gulf of Mexico	
Naples, FL	2.98
Destin, FL	4.30
St. Andrews Park, FL	4.50
Crystal Beach, FL	4.80
Gilchrist, TX	4.10
Galveston, TX	3.80
Corpus Christi, TX	5.20
Pacific Coast	
Huntington Beach, CA	5.83
San Clemente, CA	7.10
Bolsa Chica, CA	6.10
Pt. Mugu, CA	5.70
Pismo Beach, CA	7.50
San Simeon, CA	6.50
Capitola Beach, CA	4.20
Stinson Beach, CA	7.30
Wrights Beach, CA	10.40
Shelter Cove, CA	7.10
Prairie Creek, CA	7.0
Umpqua, OR	7.8

Closure depth is defined based on Hallermeier's d_1 limit [i.e., "the maximum water depth for nearshore erosion by extreme (12 hours per year) wave condition"]. The d_1 limit represents the recommended seaward limit of beach nourishment "to ensure its (the sands) inclusion in the annually very active littoral zone (Hallermeier, 1981)." This limit does not consider sand transport due to extreme storm events and thus ignores sand potentially lost to the outer profile in such scenarios.

an average of 600 feet offshore. This distance was used in the calculations to determine the area of beach profile nourishment (i.e., length of beach to be nourished multiplied by offshore distance of closure depth = beach profile area to be nourished).

AREA MEASUREMENTS

The initial response to rising sea levels is beach profile nourishment. Following this preliminary measure, it is possible that low-lying areas of the barrier may be raised to a higher elevation by sediment input to prevent submergence. This report assumes that backbarrier elevations are raised after 1 foot of sea level rise and that oceanside elevations are raised after 4 feet of sea level rise. Sediment volumes needed to raise these barrier elevations were approximated in the following manner:

- U.S.G.S. topographic maps (7.5-minute series) were obtained for each study area.
- Backbarrier areas less than 5 feet above MSL were delineated.
- Oceanside areas greater than 3 feet, but less than 15 feet above MSL, were delineated, unless the higher elevation represented a dune line. If a dune line was shown, it was included in the oceanside area measurement, as it is likely that dune elevations would be raised in concert with beach elevations to maintain the storm buffer.
- Area measurements for each delineated backbarrier and oceanside location were estimated using an engineer's ruler and the map scale. All area measurements represent the average width and length for the delineated locations. Only buildable (i.e., not marshy) areas were included. Small, isolated locations were not included, as the maintenance (e.g., dredging) costs would likely exceed associated economic benefits.

When tabulating final results, calculations for physiographically similar locations often were lumped together. Thus, the Delray Beach profile, backbarrier, and oceanside areas were summarized with the results of Boynton and Highland Beaches and Boca Raton to give the final results:

- Profile Nourishment: 1.693 million cubic yards of sand needed for one foot of sea level rise (SLR);
- Backbarrier Elevations: 0.946 million cubic yards of sand needed for one foot of elevation raising;
- Oceanside Elevations: 3.217 million cubic yards of sand needed for one foot of elevation raising.

Table 4 summarizes the above results for varying SLR scenarios.

Sand volume estimates like those given above were derived for all developed and developable coastal localities. These individual site results were then cumulated as statewide totals. Table 5 provides an example summary for the Florida (Atlantic) coast.

SAND SOURCES AND ASSOCIATED COSTS

The U.S. Army Corps of Engineers was involved in the late 1960s to mid-1970s in an inventory of the morphological and sediment characteristics of the Inner Continental Shelf (ICONS Studies) in an effort to locate sand suitable for beach nourishment endeavors. Using high-resolution seismic reflection surveys and sediment coring techniques, they performed a preliminary assessment of offshore borrow sites suitable for the restoration of nearby beaches (Duane and Meisburger, 1969) The ICONS surveys were the primary sources used in this report to locate sand sources suitable for future beach nourishment projects.

Table 4.* Sand Volume Requirements for Boynton Beach to Boca Raton, FL (including Delray Beach) to Raise the Beach/Nearshore Profile and Barrier Elevations with Sea Level Rise**

Sea Level Rise (feet)	Beach/Nearshore Profile (million yd^3)	Barrier Elevations (million yd^3)		Total (million yd^3)
		Backbarrier	Oceanside	
1	1.693	0	0	1.693
2	3.386	0.946	0	4.332
3	5.079	1.892	0	6.971
4	6.772	2.838	3.217	12.827
5	8.465	3.784	6.434	18.683
6	10.158	4.730	9.651	24.539
7	11.851	5.676	12.868	30.395
8	13.544	6.622	16.085	36.251
9	15.237	7.568	19.302	42.107
10	16.930	8.514	22.519	47.963

*Excerpted Table 30 from Florida (Atlantic) Report.
**Shore length considered for nourishment is 14.43 miles.

Table 5.* Summary of Sand Volume Requirements for the Atlantic Coast of Florida to Raise the Beach/Nearshore Profile and Barrier Elevations with Sea Level Rise

Sea Level Rise (feet)	Beach/Nearshore Profile (million yd^3)	Barrier Elevations (million yd^3)		Total (million yd^3)
		Backbarrier	Oceanside	
1	76.981	0	0	76.981
2	153.962	22.358	0	176.320
3	230.943	44.716	0	275.659
4	307.924	67.074	85.219	460.217
5	384.905	89.432	170.438	644.775
6	461.886	111.790	255.657	829.333
7	538.867	134.148	340.876	1,013.891
8	615.848	156.506	426.095	1,198.449
9	692.829	178.864	511.314	1,383.007
10	769.810	201.222	596.533	1,567.565

* Excerpted Table 32 from the Florida (Atlantic) report.

For example, the Florida Atlantic coast was studied as a part of the ICONS program. Surveys were taken covering the following areas:

- Miami to Palm Beach (Duane and Meisburger, 1969)
- Palm Beach to Cape Kennedy (Meisburger and Duane, 1971)
- Cape Canaveral (Field and Duane, 1974)
- Cape Canaveral to Georgia (Meisburger and Field, 1975)

Table 6 briefly characterizes sand located by the ICONS studies. These maps and data contained in the ICONS reports were used to identify the offshore locations of sand suitable for beach replenishment. For example, Field and Duane (1974) define sand suitable for beach nourishment in the Cape Canaveral area as "medium to coarse, well-sorted quartzsize-mollusk sand." Seismic profiling and coring suggest that such sand sources lie in large offshore shoals such as Chester Shoal, which contains an estimated sand quantity of 8.8×10^6 yd^3. Table 7 summarizes all reported Florida Atlantic sand reserves in terms of offshore location, quantity, and associated nourishment cost. The data provided in Table 7 were paramount in calculating final sand costs associated with beach nourishment.

Initial dredging costs for the Florida Atlantic coast were established at $4.00 per cubic yard, based on Bruun (1985). Bruun's paper examined some beach nourishment projects in Florida, where he noted that project costs ranged between $3 and 5.00 per cubic meter ($2.27-3.78 per cubic yard), with costs recently increasing. It is likely that dredging costs will continue to increase with future beach restoration projects, thus the higher figure of $5.00 per cubic meter (approx. $4.00 per cubic yard) was used to provide preliminary estimates of future sand costs for beach nourishment.

The $4.00 per cubic yard value was used only for sand reserves located within one mile of the shore, as dredging costs increase with greater distance offshore. The Army Corps of Engineer's "rule of thumb" for dredging cost escalation is $1.00 per cubic yard for each additional mile offshore (Weggel, personal communication, 1987). This rule only applies for sand reserves within 5 miles of the shore when a floating pipeline dredge system is used to pump the sand directly to the beach. Beyond 5 miles, the sand must be moved in two stages; dredging onto a ship for transport to the mainland, followed by truck hauling to location. Costs for this process are not clearly known, but it is estimated that at least $2.00 per cubic yard would be added to the highest floating pipeline cost. This rate is used for all cost calculations requiring sand beyond 5 miles. Table 7 summarizes sand costs based on offshore location for the Florida Atlantic coast.

Given data on offshore sand reserves and associated dredging costs, it is possible to project future costs of beach nourishment projects given various SLR scenarios. This report examines six SLR scenarios and projected costs at 20-year intervals (2000-2100) given relative sea level rises (RSLR) for each state. Table 8 indicates the RSLR for the Atlantic coast of Florida for each scenario and year studied. These RSLR estimates were multiplied by the amount of area contained in the beach profile, backbarrier, and oceanside locations to provide estimates of sand volumes needed for nourishment (Table 9). Recall that beach profiles are nourished immediately, backbarrier elevations are raised after 1 foot of SLR, and oceanside elevations are raised with 4 feet of rise. An example calculation for the state of Florida (Atlantic) is given as follows (using RSLR Scenario IV and the year 2100):

- Projected RSLR for Scenario IV by 2100 is 6.94 feet (Table 8)
- Multiply projected RSLR by the appropriate volume of sand needed to nourish 1 foot of each barrier area -

Table 6. ICONS Survey Results - Potential Offshore Sources of Sediment for Beach Nourishment

Study Area	Amount Available (million yd^3)	Type	Suitability
I. Miami to Palm Beach (Duane and (Meisburger, 1969)			Possibly suitable for short-term projects, but are easily degraded in turbulent littoral zone and may become too fine for long-term projects.
a) south of Boca Raton	201; located in offshore troughs	Mostly calcareous	
b) north of Boca Raton	380; thickly blanketed over portions of the shelf	50-50% quartz and calcareous sediments	Too fine for successful nourishment of area's beaches; not included in nourishment assessment.
II. Palm Beach to Cape Kennedy (Meisburger and Duane, 1971)	minimum of 92.2; located in ridge-like shoals	Medium to coarse calcareous sand	Sand suitable for nourishment lies in three major areas: - Capron Shoal - approx. 65.4 x 10^6 yd^3 - Indian River Shoal - approx. 10.3 x 10^6 yd^3 - Bethel Shoal approx. 16.5 x 10^6 yd^3 Other shoals in the area also may have suitable material, although evidence is currently lacking.

Table 6. Continued.

Study Area		Amount Available (million yd^3)	Type	Suitability
III.	Cape Canaveral (Field and Duane, 1974)	approx. 130; large, south-trending, cape-associated shoals	medium to coarse, well sorted quartz-mollusk sand	Well suited for nourishment. Surveyed areas show the following sand quantities: - Ohio-Hetzel Shoal (76.1×10^6 yd^3) - Chester Shoal (8.8×10^6 yd^3) - The Bull (31.6×10^6 yd^3) - Southeast Shoal (15.2×10^6 yd^3) Volumes of suitable sand in unsurveyed areas of Chester and Southeast Shoal are likely an order of magnitude larger.
IV.	Cape Canaveral to Georgia (Meisburger and Field, 1975)	minimum of 295; ten potential borrow sites (possibly 21 more sites) are identified, with each having a sand reserve from 5-178; total volumes are unknown - more study needed; located in linear shoals.	Fine to very quartz sand in shoreface; seaward of shoreface, sand is fine to medium, well sorted, predominantly quartz sand	Suitable sand was identified in the following locations: - Jacksonville (5.0×10^6 yd^3) - Mickler Landing (178.0×10^6 yd^3) - St. Augustine (7.4×10^6 yd^3) - Marineland (39.0×10^6 yd^3) - Ormond Beach (66.0×10^6 yd^3). Further study may show significantly more sand available.

Table 7. Sand Reserves and Approximate Associated Dredging Costs for the State of Florida (Atlantic Coast)

Distance Offshore (miles)	Sand Amount (million yd^3)	Cost per yd^3 (\$)	Total Cost (million \$)
< 1 mile	66	4.00	264
1-2	87	5.00	435
2-3	122.3	6.00	733.8
3-4	48	7.00	336
4-5	-	8.00	-
5-6	199.2	10.00*	1992
6-7	-	10.00*	-
7-8	97.6	10.00*	976
8-9	-	10.00*	-
9-10	15.2	10.00*	152
10-11	76.1	10.00*	761
11-12	39.0	10.00*	390
12-13	-	10.00*	-
13-14	175	10.00*	1750

* At distances > 5 miles offshore, it is highly unlikely that a floating pipeline dredge would be used. Rather, sand would probably be moved in two stages; dredging into a ship for transport to mainland, followed by truck hauling to location. Costs for this process are not clearly known, but it is estimated it would add at least \$2.00 per yd^3 to the highest floating pipeline cost.

Table 8. Amount of Sea Level Rise for Various Year/Scenario Combinations (in feet)*

	Scenario					
Year	I	II	III	IV	V	VI
2000	.12	.14	.17	.19	.22	.24
2020	.35	.50	.64	.79	.93	1.08
2040	.66	1.03	1.39	1.76	2.13	2.50
2060	1.04	1.73	2.42	3.11	3.80	4.49
2080	1.49	2.60	3.72	4.84	5.95	7.06
2100	2.01	3.65	5.30	6.94	8.57	10.22

Scenarios I, II, III (NRC, 1987)
Scenarios IV, V, VI (EPA, 1986)
*Relative sea-level rise has averaged 2.2 mm/yr (baseline record from Mayport and Key West, Florida tide guages). 1986 is base level year for projections.

-6.94 feet (RSLR) x Table 5 value for Beach/Nearshore Profile (76.981) = 534.248 million yd^3

-[6.94 feet (RSLR) - 1 foot] x Table 5 value for backbarrier elevations (22.358) = 132.806 million yd^3

-[6.94 feet (RSLR) - 3 feet] x Table 5 value for oceanside elevations (85.219) = 335.762 million yd^3.

o Add the sand volumes given above (534.248 + 132.806 + 335.762 = 1,002.818 million yd^3) to derive the total sand volumes needed to protect the barriers from encroaching seas (Table 9).

After determining sand volumes needed for each SLR scenario and associated year, nourishment costs are calculated. Initial dredging costs were used to determine final costs until all sediment supplies within one mile of the shore were exhausted. In the case of Florida, \$4.00 per yd^3 was used to project costs for the first 66 million yd^3 of sediment (see Table 7). After exhausting these nearby sand reserves, the cost escalation function was employed for sand each additional mile offshore. For example, Florida's Scenario IV projects that by the year 2100, 1,002.818 million yd^3 of sand will be needed for beach nourishment. All of Florida's recorded offshore sand reserves would be exhausted by such a request; however, costs were calculated assuming the availability of sand. A sample cost calculation is given as follows:

Scenario IV, year 2100

1,002.818 million yd^3 of sand needed for nourishment (see Table 9)...

1,002.818 yd^3
- 66.000 yd^3 @ \$4.00/yd^3 (sand w/in 1 mile; see Table 7)
936.818 yd^3
- 87.000 yd^3 @ \$5.00/yd^3 (sand 1-2 miles; see Table 7)
849.818 yd^3
- 122.300 yd^3 @ \$6.00/yd^3 (sand 2-3 miles; see Table 7)
727.518 yd^3
- 48.000 yd^3 @ \$7.00/yd^3 (sand 3-4 miles; see Table 7)
679.518 yd^3 @ \$10.00/yd^3 (sand >5 miles; see Table 7)

Table 9. Sand Volumes Required to Raise the Beach/Nearshore Profile and Barrier Elevations for the Florida Atlantic Coast (million yd^3)

	Scenarios						
Year	I	II	III	IV	V	VI	LST*
2000	9.238	10.777	13.087	14.626	16.936	18.475	2.800
2020	26.943	38.490	49.268	60.815	71.592	83.139	6.800
2040	50.807	79.290	107.004	135.487	189.234	225.989	10.800
2060	80.060	133.177	218.042	286.586	355.130	550.650	14.800
2080	114.702	235.921	347.183	615.246	820.105	1,024.964	18.800
2100	177.314	340.230	700.142	1002.818	1,303.647	1,608.168	22.800

*LST is longshore sediment transport. Average annual rates vary along the Florida Atlantic Coast so a representative figure of 200,000 yd^3 is used for illustrative purposes.

Given the above, total sand costs for Scenario IV, year 2100, for the Florida Atlantic coast are $8,563.980 million dollars (Table 10).

Tables 9 and 10 also provide sand volume and cost estimates based on average annual longshore transport rates (200,000 yd^3/year) for the Florida Atlantic coast. It is obvious from these figures that sand removed from the system by longshore transport is insignificant compared to that required to compensate for accelerated sea level rise.

Sand costs for the Atlantic coast of Florida were derived assuming equal access to offshore sand reserves for all coastal locations, as it was beyond the scope of this research to evaluate sand supplies and costs on a site-specific basis. In reality, suitable borrow material is scattered along the coastline; some areas have sand directly offshore, while other sites are far removed from available supplies. Therefore, the equal access assumption made in this report may underestimate true sand costs, as sand hauling to distant locations is not adequately examined.

Table 10. Cost of Raising the Beach/Nearshore Profile and Barrier Elevations for the Florida (Atlantic) Coast ($ millions)*

	Scenarios						
Year	I	II	III	IV	V	VI	LST**
2000	36.952	43.108	52.348	58.504	67.744	73.900	11.200
2020	107.772	153.960	197.072	243.260	291.960	349.695	27.200
2040	203.228	330.450	469.020	611.435	916.404	1,136.934	43.200
2060	334.300	599.885	1,089.252	1,511.802	2,087.100	4,042.300	59.200
2080	507.510	1,196.526	2,007.630	4,688.260	6,736.850	8,785.440	75.200
2100	844.884	1,938.100	5,537.220	8,563.980	11,572.2730	14,617.480	91.200

*These cost figures assume that the borrow sand is fully compatible in size with the native sand and will remain on the active beach profile; this is a conservative assumption.

**LST is longshore sediment transport (see footnote for Table 7).

CHAPTER 3

NATIONWIDE RESULTS

The U.S. coastline can be divided on the basis of physiographic regions for discussion purposes. The New England states typically have small sandy beaches, often consisting of sand spits. Massachusetts has the largest number of such recreational beaches (Table 11), but those along the Rhode Island coast are perhaps the most urbanized and have been subject to severe damage during historical hurricanes.

The Mid-Atlantic coast, which extends from New York to Virginia, is in general the most urbanized shore in the country except for parts of Florida and southern California. The recreational beaches in New York and northern New Jersey serve as the playgrounds for some 15 million people in the greater New York metropolitan area. Presently, pollution from human waste is adversely impairing their recreational value, but beach erosion has been a chronic problem, and many nourishment projects have already been completed and others are planned. Farther south, there are more open stretches of coast (parklands, reserves, etc.) so that the approach of holding the line by beach fill would be city-specific (e.g., Virginia Beach, VA, Ocean City, MD) rather than island-wide (e.g., Long Beach Island, NJ).

The U.S. southeastern coast (North Carolina to Florida) is the least urbanized along the Atlantic coast, but this area has the largest growth potential because of the greatest availability of beachfront property. The Outer Banks of North Carolina constitute a long chain of barrier islands with development spread out over long distances (Table 11). While an increasing number of multi-story condominiums are being built, the traditional type building is the wooden, single-family house that can be readily moved. Therefore, the retreat alternative becomes more attractive than beach stabilization in many areas. This alternative is plausible to a less extent in South Carolina and Georgia, but many islands are already too urbanized for this approach (e.g., Hilton Head, S.C.). Also, the barrier islands in the Georgia bight (southern South Carolina to northern Florida) are generally higher in elevation, much wider, and more stable than the microtidal barriers found elsewhere along the Atlantic coast (Leatherman, 1988).

Florida should be considered separately from the others as its immense coastline is the single most important feature of the state. Almost 300 miles are considered for beach nourishment along the Atlantic coast, and about 250 miles on the Gulf will require sand fill with accelerated sea level rise. It could be argued that Florida has the most important beaches in the United States because it serves as a national and even international resort area. Recreational beaches are the number one source of revenue, and state officials are considering spending tens of millions of dollars each year for beach nourishment. The Miami Beach project, completed in 1980 at a cost of $65 million for 10 miles of beach, perhaps represents the scale and magnitude of future such projects along this rapidly urbanizing coast, which is becoming dominated by the high-density, high-rise type of development.

The Gulf Coast is the lowest-lying area in the U.S. and consequently is the most sensitive to small changes in sea level. One of the earliest extensive beach nourishment projects undertaken in the U.S. was in Harrison County, Alabama, in the 1950s. The beaches have greatly narrowed since this time, and renourishment is now required. Louisiana has the most complex coastline in the region and also has the distinction of having the most rapid rate of beach erosion in the nation. While a number of islands are included on the state list for nourishment (Table 11), much of this proposed work will probably never be undertaken since it is uneconomical under today's conditions. There are only two recreational beaches in the State of Louisiana--Grand Isle and Holly Beach. While Grand Isle was recently nourished, it is unlikely that the economics (relative high cost of sand fill vs. value of property to be protected) will make future projects feasible with accelerated sea level rise. Texas has the most extensive sandy coastline in the Gulf, but much of the area is little inhabited. Clearly the City of Galveston will be maintained, but the nearly century-old seawall has been most effective in this regard largely at the expense of the beach. Elsewhere, beach nourishment is probably not the most viable alternative as much land on the barrier islands is generally available for relocation.

Table 11. Sites Investigated for Sand Fill with Sea-Level Rise

State/Site	Miles of Shoreline	Sand Volume Needed (million yd^3)		
		Profile	Bayside	Oceanside
Maine-Higgins Beach	0.62	0.303	----	----
State Total	30.87		----	3.139
New Hampshire beaches (Total)	8.91	5.229	----	1.220
Massachusetts-Humarock Beach	2.75	0.967	----	----
Siasconset	1.70	0.333	----	----
State Total	100	27.390		137.984
Rhode Island beaches (Total)	27.42	6.970	----	3.308
Connecticut beaches (Total)	63.51	43.467	----	7.663
New York-Southampton Beach	7.05	2.756	----	----
State Total	120	46.910	3.168	30.272
New Jersey-Long Beach Island	18.03	5.289	3.778	2.936
State Total	125	36.668	26.180	20.362
Delaware-Rehoboth Beach	1.55	0.243	----	----
Dewey Beach	1.59	0.249	0.132	0.189
Bethany/South Bethany	2.95	0.462	----	1.095
Fenwick Island	1.12	0.175	0.262	0.219
North Bethany	2.73	0.426	----	----
State Total	9.94	1.555	0.394	1.503
Maryland-Ocean City (Total)	8.94	2.447	----	4.124
Virginia-Wallops Island	5.89	5.759	----	0.691
Virginia Beach	5.89	1.728	----	3.995
Sand Ridge	5.21	2.241	----	1.268
State Total	16.99	9.728		5.954
North Carolina-Currituck Banks	2.84	1.667	----	1.944
Currituck Spit	29.47	17.288	----	14.403
Nags Head area	19.82	11.627	----	7.935
Buxton	0.95	0.556	----	0.611
Bogue Banks	22.67	6.207	0.519	0.241
Topsail Island/ Beach	21.14	4.547	1.176	1.326
Lee Island complex	3.60	0.774	0.141	0.281
Figure Eight Island	3.64	0.774	0.096	0.356

State/Site	Miles of Shoreline	Area (million yd^3) Profile	Bayside	Oceanside
Wrightsville Beach	4.36	0.852	----	0.852
Wilmington Beach area	6.44	1.133	----	1.007
Long Bay area	25.57	4.500	----	----
Bald Beach/ Island	2.46	0.433	----	----
State Total	142.96	50.358	1.932	28.956
South Carolina-The Strand	20.45	3.000	----	7.600
Myrtle Beach	9.19	2.007	----	0.581
Magnolia Beach	5.19	0.879	----	1.411
Pawley's Island	3.30	0.472	----	0.129
Debidue Beach	3.66	0.979	----	1.098
Capers Island	3.03	2.370	----	1.538
Dewees Island	2.27	2.756	----	0.524
Isle of Palms	1.02	6.380	----	2.839
Sullivan's Island	3.69	3.900	----	1.499
Folly Beach	5.25	7.848	----	1.106
Kiawah Island	7.42	9.364	----	5.448
Seabrook Island	2.14	2.427	----	4.134
Edisto Beach	5.51	4.850	----	1.636
Hunting Island	5.70	13.601	----	3.096
Fripps Island	2.71	4.634	----	1.766
Hilton Head	12.75	39.134	----	9.593
State Total	93.28	104.601	----	43.998
Georgia-Tybee Island	2.65	2.738	----	1.400
Sea Island	3.46	3.579	----	1.084
St. Simons Island	2.54	2.620	----	0.759
Jekyll Island	7.44	7.685	----	6.129
State Total	16.09	16.622	----	9.372
Florida-Amelia Island	10.83	3.178	----	1.271
Seminole/Manhattan Beaches	2.78	0.762	----	0.436
Jacksonville area	5.83	1.597	----	2.384
Ponte Vedra-Vilano Beach	23.90	6.076	----	4.674
Anastasia Island	10.13	3.170	----	2.378
Summer Haven-Beverly Beach	14.96	3.511	----	3.511
Flagler Beach	5.26	1.440	----	1.133
Ormond Beach area	12.42	3.887	----	6.439
Daytona Beach	8.14	2.548	----	3.602
Wilbur-by-the-Sea	5.25	1.640	----	1.128
New Symrna Beach	4.15	1.379	----	1.839
South of Symrna Beach	17.33	5.761	----	3.816
Cocoa Beach	8.86	3.120	----	6.413
Eau Gallie Beach	11.10	3.038	3.630	9.767

State/Site	Miles of Shoreline	Area (million yd^3)		
		Profile	Bayside	Oceanside
South of Melbourne Beach	28.12	7.700	4.467	8.867
Vero Beach/Riomar	3.96	1.084	1.037	1.998
South of Vero Beach	15.26	4.179	1.490	1.987
Hutchinson Island	13.31	3.645	0.956	1.687
Jupiter Island	10.10	2.764	0.387	2.307
South of Jupiter Island	11.78	1.843	0.567	3.869
Palm Beach-Lake Worth Inlet	15.50	2.427	0.660	3.306
Boynton & Delray Beaches	14.43	1.693	0.946	3.217
Deerfield & Hillsboro Beaches	5.36	0.838	----	1.220
Pompano Beach	3.84	0.752	----	1.353
Ft. Lauderdale	5.70	1.115	----	2.085
Hollywood/Golden Beach	9.53	1.490	1.558	0.932
Miami Beach area	9.03	1.325	5.154	1.670
Virginia Key	1.80	1.548	0.589	0.352
Key Biscayne	4.03	3.471	0.917	1.578
Atlantic Coast Total	292.69	76.981	22.358	85.219
Perdido Key	5.44	0.850	0.252	1.280
Santa Rosa Island	7.84	1.533	0.479	1.851
Moreno Point	24.36	4.760	----	4.079
Laguna-Biltmore Beach	26.48	5.178	----	4.332
Mexico Beach-Beacon Hill	4.73	1.300	----	1.111
St. Joseph's Spit	4.32	1.267	----	0.845
Money Beach-Indian Peninsula	6.08	2.972	----	1.025
St. George Island	10.70	1.674	2.378	2.331
Dog Island	6.86	1.073	----	0.871
St. Teresa Island-Lighthouse Point	6.91	1.081	----	1.036
Honeymoon Island	0.95	0.518	0.292	0.278
Clearwater Beach	2.82	1.545	----	0.742
Bellair Shores-John's Pass	13.67	7.487	0.757	2.520
Treasure Island	3.20	2.191	0.896	0.678
Long Key	4.13	2.180	1.119	0.727
Cabbage Key	1.14	0	0.501	0.200
Mullet Key	4.28	1.674	0.188	0.591
Anna Maria Key	7.14	5.306	1.828	0.802
Longboat Key	9.40	2.206	1.648	1.857
Lido Key	2.39	0.560	0.584	0.327
Siesta Key	6.08	1.427	0.867	2.707
Casey Key	6.36	1.369	----	0.622
Venice Beach	3.67	0.862	----	2.419
Manasota Key	11.29	2.649	----	1.787
Knight/Don Pedro Islands	6.32	2.474	1.299	0.761
Gasparilla Island	5.87	2.526	1.326	0.837

State/Site	Miles of Shoreline	Area (million yd^3) Profile	Bayside	Oceanside
Cayo Costa	7.12	3.064	1.115	1.754
North Captiva Island	2.84	1.833	0.678	0.167
Captiva Island	4.68	3.019	0.497	0.560
Sanibel Island	12.16	10.224	3.632	2.428
Fort Meyers	6.53	5.111	0.959	1.022
Bonita Beach	5.38	3.997	----	0.316
Naples Park	4.47	1.923	----	0.313
Naples	7.86	4.611	0.585	4.071
Keewatin Island	5.00	2.542	----	0.553
Marco Island	2.46	2.311	1.848	1.011
Key West	0.57	0.500	----	3.250
Gulf Coast Total	251.50	95.797	23.728	52.061
Alabama-Gulf Shores	3.86	0.756	----	1.058
Morgan Peninsula	18.00	3.520	----	----
Dauphin Island	6.26	1.224	----	2.013
Dauphin Island-COBRA	7.95	1.556	----	0.778
State Total	36.07	7.056	----	3.849
Mississippi-Pascagoula	2.16	0.633	----	3.852
Belle Fontaine area	5.49	1.611	----	1.074
Harrison County	26	7.627	----	5.519
Hancock County	9	2.640	----	1.193
State Total	42.65	12.511	----	11.638
Louisiana-Bastian Bay complex	18.92	18.500	2.380	----
Grande Terre Islands	4.85	5.215	1.858	----
Grande Isle	7.20	4.222	3.419	----
Caminada Pass-Belle Pass	13.28	9.736	2.600	----
Timbalier Islands	16.04	15.685	3.137	----
Isles Dernieres	17.92	24.526	3.504	----
Holly Beach	7.20	9.852	1.407	----
State Total	85.41	87.736	18.305	----
Texas-Bolivar Peninsula	18.45	10.822	21.511	----
Galveston Island	28.39	11.104	32.150	5.074
Follets Island	9.81	4.413	3.907	----
Surfside Beach	4.15	1.622	1.793	----
Bryan Beach/Brazos Spit	9.94	2.917	8.519	----
Sargent Beach East	4.45	2.437	0.870	----
Sargent Beach	2.78	1.333	0.817	----
Matagorda Peninsula	50.68	16.855	35.860	----
Matagorda Island	13.13	5.903	----	15.693
St. Joseph Island	18.96	10.010	----	18.739
Mustang Island	15.55	7.906	4.600	12.107
North Padre Island	5.2[illegible]	2.273	3.611	5.267
North Padre Island-COBRA	7.03	3.435	----	9.834

South Padre Island-COBRA	29.41	11.504	----	18.770
South Padre Island	5.38	1.893	----	2.789
Brazos Island/Boca Chica	6.40	2.504	----	1.708
State Total	229.79	96.931	113.638	89.981
California-Ocean Beach	3.50	1.028	----	----
Santa Barbara	2.20	0.644	----	----
Carpinteria	1.36	0.400	----	----
Buenaventura State Park	2.84	0.833	----	----
Oxnard Beach	2.27	0.667	----	----
Malibu/Carbon Beaches	2.46	0.722	----	----
Pacific Palasades	2.08	0.611	----	----
Santa Monica/Venice Beach	5.40	1.583	----	----
Dockweller/Manhattan State Park Beach	6.36	1.867	----	----
Hermosa Beach	1.78	0.522	----	----
Redondo Beach	2.01	0.589	----	----
Long Beach	4.05	1.189	----	----
Sea Beach	0.98	0.289	----	----
Sunset Beach	1.95	0.572	----	----
Huntington Beach	3.60	1.056	----	----
Newport Beach	5.17	1.517	----	----
Laguna Beach	1.55	0.456	----	----
Capistrano Beach	2.88	0.844	----	----
Oceanside	2.94	0.861	----	----
Carlsbad	2.70	0.792	----	----
Solona Beach/Delmar	3.98	1.167	----	----
La Jolla Beach	1.14	0.333	----	----
Mission Beach	3.50	1.028	----	----
Silver Strand	10.04	2.944	----	----
Imperial Beach	1.33	0.389	----	----
State Total	78.07	22.903	----	----
Oregon-Newport	3.56	1.810	----	----
State total	27.56	14.012	----	----
Washington-Beach Peninsula	20.50	14.032	----	----
State total	48.36	33.101	----	----
Hawaii-Waikiki Beach	2.97	1.744	----	----
State total	64.24	37.722	----	----

The Pacific or West Coast can be divided into two sections -- southern California and the rest. Southern California, which extends roughly from Santa Barbara to San Diego, probably represents the most modified coastline in the county (although some could argue the same is true of northern New Jersey). This semi-arid to arid desert-land has been transformed into one of the largest population centers in the U.S., and the explosive growth is still occurring. Because of extensive and widespread nourishment projects, the beaches are reportedly wider today than they were a century ago. This is the only area in the country that has successfully reversed the long-term trend of shore recession through coastal engineering projects (largely beach nourishment). Considering the value of this real estate, potential growth factor, and history of coastal projects, these public recreational beaches will undoubtedly be maintained in the future.

Northern California, Oregon, and Washington are characterized by more cliffed and rocky coastlines. Sandy beaches occur as small pockets between headlands or as sandy spits. Owing to their general inaccessibility to large numbers of people, beach nourishment will probably be restricted to projects that incorporate inlet channel dredging as an important benefit in the total project of sand transportation.

The beaches in Hawaii are world renowned. The famous Waikiki Beach has been nourished for quite some time. Fortunately, most of the beaches are protected from direct attack of oceanic waves by the offshore coral reefs, which also serve as the source of the white, coralline sand to the adjacent beaches. As long as the coral reefs are able to maintain pace with accelerated sea level rise, it is believed that there will be plentiful coral production to be broken up and moved onshore to naturally nourish the sandy beaches. However, state officials are not relying upon this assumption, and sand sources from other areas (e.g., countries) are being assessed for its suitability and compatibility with the native beach sand.

The quantity of sand necessary to hold the shoreline in place was assessed on a state-by-state basis for various sea level rise scenarios (Table 12). This analysis indicates that Florida would have the greatest demand for sand not only to nourish the beach, but also to raise the low-lying surface elevations. If the higher scenario values are realized, then Table 12 indicates that Texas would have the second highest requirement for sand, followed by South Carolina. In practice, the Texas "requirements" will probably not be met as previously discussed, while the quantities required in South Carolina must be considered more seriously due to the present value and continued construction along this coastline.

Nationwide estimates of sand quantities required with accelerated sea-level rise are arrayed in Table 13. It is apparent that tremendous quantities of good quality sand will be necessary to maintain the nation's major recreational beaches. Almost all of this sand must be derived from offshore, but to date only enough sand has been identified to accommodate the two lowest scenarios over the long term. Even in these cases, the offshore sand is not evenly scattered along the U.S. coastline, so that some areas will run out of local (the least expensive) sand in a few decades. The costs of sand fill presented in Tables 14 and 15 are based on current expense of offshore dredging and pumping onshore of locally derived material. Obviously, the costs will increase with inflation, but more importantly the expense could be greatly underestimated if sand must be acquired from considerable distance from the beach requiring nourishment.

The ranges of costs are arrayed by state for scenarios I to IV (Table 14). The sand cost not only includes the quantity required, but also the current statewide cost of such nourishment activities. Since the cost per cubic yard has been traditionally high in Texas, this state is projected to incur the highest expense. While considerable quantities are also required for California, the costs are by comparison quite low owing to the local availability of good sandy material at very reasonable rates. Table 15 summarizes the nationwide costs of sand fill required with accelerated sea level rise. The costs do not seem too unreasonable for the next several decades considering past expenditures for shoreline stabilization and the U.S. GNP. However, the costs tend to increase in an exponential fashion due to the increasing rate of sea level rise through time.

Table 12. Quantity of Sand by State and Use for Baseline, Half, One and Two Meters by Year 2100 (in million yd^3)

State	Baseline (12 cm)				Half Meter (Scenario I)			
	Profile	Bay	Ocean	Total	Profile	Bay	Ocean	Total
Maine	5.790	--	--	5.790	29.842	--	--	29.842
New Hampshire	2.039	--	--	2.039	9.725	--	--	9.725
Massachusetts	10.667	--	--	10.667	62.358	--	--	62.358
Rhode Island	2.718	--	--	2.718	15.334	--	--	15.334
Connecticut	16.952	--	--	16.952	86.065	--	--	86.065
New York	18.295	--	--	18.295	98.044	--	--	98.044
New Jersey	11.706	6.413	1.954	20.073	79.541	35.378	--	114.919
Delaware	0.606	--	--	0.606	3.654	0.532	--	4.196
Maryland	0.954	--	--	0.954	5.750	--	--	5.750
Virginia	3.794	--	--	3.794	25.098	--	--	25.098
North Carolina	19.640	--	--	19.640	93.666	--	--	93.666
South Carolina	40.794	--	--	40.794	257.318	--	--	257.318
Georgia	6.482	--	--	6.482	38.397	--	--	38.397
Florida-Atlantic	30.023	--	--	30.023	154.732	22.582	--	177.314
Florida-Gulf	37.361	--	--	37.361	200.216	25.864	--	226.080
Alabama	2.752	--	--	2.752	14.747	--	--	14.747
Mississippi	4.879	--	--	4.879	26.148	--	--	26.148
Louisiana	391.720	--	--	391.720	449.208	75.417	--	524.625
Texas	37.803	--	--	37.803	260.744	192.048	--	452.792
California	8.932	--	--	8.932	43.516	--	--	43.516
Oregon	5.465	--	--	5.465	15.132	--	--	15.132
Washington	12.909	--	--	12.909	35.749	--	--	35.749
Hawaii	14.712	--	--	14.712	67.522	--	--	67.522

Table 12. (continued)

	One Meter (Scenario II)				Two Meters (Scenario IV)			
	Profile	Bay	Ocean	Total	Profile	Bay	Ocean	Total
Maine	54.191	--	--	54.191	103.038	--	--	103.038
New Hampshire	18.353	--	--	18.353	35.505	--	--	35.505
Massachusetts	107.212	--	--	107.212	196.920	--	--	196.920
Rhode Island	26.765	--	--	26.765	49.696	--	--	49.696
Connecticut	157.351	--	--	157.351	299.922	--	--	299.922
New York	174.978	--	--	174.978	328.846	--	--	328.846
New Jersey	128.766	70.540	21.491	220.797	227.516	141.075	76.312	444.903
Delaware	6.204	1.178	1.503	8.885	11.320	2.474	6.433	20.227
Maryland	9.764	--	4.083	13.847	17.814	--	17.651	35.465
Virginia	41.052	--	7.264	48.316	72.960	--	26.793	99.753
North Carolina	176.757	4.849	--	181.606	341.931	11.186	109.743	462.860
South Carolina	428.864	--	48.398	477.262	773.001	--	193.151	966.152
Georgia	65.657	--	8.903	74.560	120.343	--	39.737	160.080
Florida-Atlantic	280.981	59.249	--	340.230	534.248	132.806	335.763	1002.818
Florida-Gulf	357.323	64.777	--	422.100	671.537	142.605	208.765	1022.907
Alabama	26.319	--	--	26.319	49.463	--	15.434	64.897
Mississippi	46.666	--	--	46.666	87.702	--	46.668	134.370
Louisiana	593.095	105.437	--	698.532	880.869	165.477	--	1046.346
Texas	419.711	378.415	119.675	917.801	737.645	751.147	414.812	1903.604
California	81.077	--	--	81.077	156.427	--	--	156.427
Oregon	38.112	--	--	38.112	84.072	--	--	84.072
Washington	90.034	--	--	90.034	198.606	--	--	198.606
Hawaii	129.386	--	--	129.386	253.492	--	--	253.492

Table 13. Nationwide Estimates of Sand Quantities Required with Sea Level Rise (million yd^3)

	Scenarios					
Year	I	II	III	IV	V	VI
2000	145.634	166.770	187.645	208.417	229.727	250.470
2020	404.697	531.097	654.255	777.742	900.743	1041.429
2040	749.914	1067.874	1394.713	1850.035	2272.343	2658.815
2060	1155.129	1925.232	2667.664	3390.477	4315.144	5428.242
2080	1772.567	2751.612	4314.381	6021.119	7469.329	9251.228
2100	2424.337	4345.477	6767.643	9070.906	11356.659	13655.708

Table 14. Range of Cost of Sand Fill for Scenarios I to IV (50 to 200 cm Sea-Level Rise) for Each State ($ millions)

State	2000	2020	2040	2060	2080	2100
Maine	7.1-11	21-47	39-105	62-185	88-287	119-412
New Hampshire	2.1-3.6	6.5-15	12-35	20-63	29-99	39-142
Massachusetts	32-49	92-187	167-406	260-704	365-1084	490-1546
Rhode Island	5.9-9.2	17-36	24-77	49-135	69-209	92-298
Connecticut	28-50	89-203	167-454	263-806	381-1255	516-1800
New York	48-74	136-298	254-663	398-1164	571-1804	770-2581
New Jersey	47-64	127-231	226-664	342-1240	644-2305	902-3492
Delaware	2.0-2.9	5.6-11	10-24	16-49	22-102	34-162
Maryland	2.4-3.4	6.6-13	12-28	18-49	26-127	34-213
Virginia	15-20	40-74	72-158	109-271	152-522	201-798
North Carolina	35-60	109-261	208-596	331-1090	483-2057	656-3240
South Carolina	80-118	231-433	410-927	626-1600	876-2900	1158-4348
Georgia	11-15	29-59	53-126	82-220	116-416	153-640
Florida-Atlantic	37-59	108-243	203-542	320-1466	474-3981	787-7746
Florida-Gulf	50-77	142-312	264-690	421-1416	646-2643	904-4092
Alabama	3.7-5.6	10-23	17-51	30-89	44-168	59-260
Mississippi	4.5-6.9	13-28	24-62	37-109	53-229	72-370
Louisiana	219-250	562-755	1038-1621	1526-2628	2056-3832	2623-5232
Texas	179-251	493-888	879-3000	1318-5863	2922-11437	4188-17608
California	10-16	29-70	55-157	88-279	128-434	174-626
Oregon	0-4.5	3.9-29	12-74	24-140	40-228	61-336
Washington	0-11	9.3-68	28-175	57-331	95-539	143-794
Hawaii	17-32	53-136	104-313	168-560	245-877	338-1267

Table 15. Nationwide Estimates of Cost of Sand Fill Required with Sea Level Rise ($ millions)

Year	I	II	III	IV	V	VI
2000	837	958	1,073	1,192	1,310	1,428
2020	2,333	3,032	3,722	4,418	5,112	5,911
2040	4,277	6,073	7,896	10,956	13,497	15,873
2060	6,564	11,419	15,949	20,457	26,510	33,885
2080	10,524	15,874	26,528	37,525	47,672	59,502
2100	14,512	26,745	42,765	58,002	71,151	88,379

CHAPTER 4

CONCLUSIONS

This study represents the first estimation of sand requirements necessary to stabilize the United States coastline with accelerated sea-level rise. Both the volume of sand and associated costs to nourish the beach profile and maintain low-lying surface elevations relative to sea level have been considered. A number of assumptions have been made to make these calculations so that the numbers will be refined as more data becomes available.

The cost to stabilize the coast through the "soft" engineering approach of sand filling ranges from approximately $2.3 billion to $5.9 billion for Scenarios I to VI by the year 2020 on a nationwide basis. Considering the enamorous value of coastal property (e.g., Miami Beach alone is valued at over $1 billion), it is safe to assume that the densely developed areas will be nourished and maintained. What is unclear is at what point moderate-density areas will be forced by economic considerations to choose another approach (e.g., retreat from the eroding beach). The next step will be to refine these estimates by completing the analysis on a community-level basis and then comparing these costs with the value of the affected coastal property.

REFERENCES

Bruun, P. 1985. Cost-Effective Coastal Protection With Reference to Florida and the Carolinas, U.S.A. Journal of Coastal Research, v.1, 47-55.

Duane, D.B. and E.P. Meisburger. 1969. Geomorphology and Sediments of the Nearshore Continental Shelf, Miami to Palm Beach, Florida - U.S. Army, Corps of Engineers, TM - No. 29.

Field, M.E. and D.B. Duane. 1974. Geomorphology and Sediments of the Inner Continental Shelf, Cape Canaveral, Florida. U.S. Army, Corps of Engineers, T.M. - No. 42.

Florida Department of Natural Resources. 1988. Florida's Beach Restoration Management Plan.

Hallermeier, R.J. 1981. A Profile Zonation for Seasonal Sand Beaches from Wave Climate. Coastal Engineering, v. 4, 253-277.

Hoffman, J.S., J.B. Wells, and J.G. Titus, 1986, Future global warming and sea level rise, in Iceland Coastal and River Symposium, Reykjavik, Iceland, p. 245-266.

Leatherman, S.P. 1985, Geomorphic effects of accelerated sea-level rise on Ocean City, Maryland. In Potential Impacts of Sea Level Rise on the Beach at Ocean City, Maryland, J.G. Titus, ed. Washington, D.C.: U.S. Environmental Protection Agency34 pp.

Leatherman, S.P., 1986, Effect of Accelerated Sea-Level Rise on Coastal Ecosystems, U.S. Senate Publication, S.Hrg. 99-723, Washington, DC, p. 141-153.

Leatherman, S.P. 1988. Barrier Island Handbook, University of Maryland, College Park, MD, 92 pp.

Lyles, S.D., L.E., Hickman, Jr., and H.A. Debaugh, Jr., 1987, Sea level variations for the United States, 1855-1986, NOAA National Ocean Service Report, Rockville, MD, 182 pp.

Meisburger, E.P. and D.B. Duane. 1971. Geomorphology and Sediments of the Inner Continental Shelf, Palm Beach to Cape Kennedy, Florida. U.S. Army Corps of Engineers, T.M. - No. 34.

Meisburger, E.P. and M.E. Field. 1975. Geomorphology, Shallow Structure, Sediments of the Florida Inner Continental Shelf, Cape Canaveral to Georgia. U.S. Army Corps of Engineers, T.M. - No. 54.

National Research Council, 1987, Responding to Changes in Sea Level: Engineering Implications, National Academy of Sciences, Washington, DC, 148 pp.

Weggel, R. 1987. Personal Communication.

U.S. Army Corps of Engineers, 1971, National Shoreline Study, Washington, DC,59 pp.

THE COST OF DEFENDING DEVELOPED SHORELINES ALONG SHELTERED WATERS OF THE UNITED STATES FROM A TWO METER RISE IN MEAN SEA LEVEL

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CHAPTER 1

INTRODUCTION[1]

Mean sea level is rising in those regions of the world not previously or recently glaciated, not near present plate boundaries, and not currently subjected to man-caused subsidence. The rise in sea level is eustatic in nature and worldwide records suggest an overall rise of about 12 cm over the last 100 years (Fairbridge & Krebs, 1962; Gornitz et al., 1982).

Measurements of sea level rise along the coastal margins of the United States show substantial local variability, but reasonable averages over the last century suggest a 30-cm rise along the East Coast of the U.S., an 11-cm rise along the West Coast, and rises ranging from 20 to 100 cm per century along the Gulf of Mexico.

The above estimates of sea level rise are averages based on analysis of available records gathered at specific locations such as New York, New York, and Atlantic City, New Jersey, over recent decades as well as readings made at tide gaging stations currently in operation. The estimates filter out the shorter term (2-7 years) meteorological fluctuations.

Geological data support the observed indications of recent sea level rise and suggest a fluctuating but persistent rise over the last 1500 years with even more rapid rates of rise extending back over the last 6000 years (Fairbridge, 1961).

Beyond past and present rates of rise, there is a growing belief, based on theoretical evaluations of the potential causes of sea level rise, that a sustained or, more likely, an accelerated rate of sea level rise can be expected in the future. The cause of the projected rise is global warming due to the "greenhouse" effect (assisted by ozone depletion), which leads to melting of Alpine glaciers, ice sheets, and ice caps on a global scale, accompanied by thermal expansion of the oceans.

Projections of future sea levels vary based on the assumptions used. Estimates of the global rise by the year 2100 generally are between 50 and 200 cm, although Hoffman (1985) concludes that a 350-cm rise is possible (Titus, 1986; Revelle, 1983; Meier et al., 1985). Because of the quantitative uncertainties and probabilities involved in such a prediction, the Committee of Engineering Implications of Changes in Relative Mean Sea Level (National Research Council, 1987) suggests that three plausible variations in eustatic sea level rise be assumed for design purposes, all of which project an increasing rate of rise relative to the present and produce rises of 50, 100, and 150 cm by the year 2100.

Even recognizing that tide-gage data are subject to influences that tend to "degrade the data" and that estimates of the future eustatic sea level are based on estimates of factors such as glacial thickness that are not well known, the projections of accelerated sea level rise cannot be disregarded. In the United States there is an enormous and growing investment of population, facilities, and real estate in the zone along the Atlantic, Pacific, and Gulf of Mexico coastal margins. Moreover, the postulated climatic and oceanic models on which increasing rates of eustatic sea level rise are based are sufficiently well developed to assume that the physical and financial risks to coastal communities, facilities, and environments can be realistically estimated, and that many areas are vulnerable to undesirable changes caused by a rising sea level.

The effects of sea level rise on the coastal zone would include effects on physical processes such as: changes in weather patterns; higher storm surges; increased storm damage; shoreline erosion; increased flood frequencies due to backwater effects; changes in river courses and flow rates; increased sedimentation; shoaling and scouring in inlets; increased need to dredge waterways; loss of agricultural land; increased landslides; changing offshore current speeds and directions; land subsidence; higher waves; and more frequent barrier island washover. There could be major influences on systems, facilities, and infrastructure such as: buried utilities, subway systems, municipal storm and sanitary sewers, transportation systems (roadways, railways, etc.), water treatment plants, landfills, drainage patterns, water supply systems, ground water supplies, bridges, and coastal navigation and harbor improvements. Construction-related activities impacted might include: dredging, tunnelling, drainage, elevated water tables and dewatering, foundation elevations, tidal energy projects, increased construction costs, and beach nourishment sand sources. Environmental impacts include: changes in wetland area boundaries, saltwater intrusion, increased energy consumption for pumping, ecological changes, evaporation ponds, coastal vegetation, inundation, and loss of habitat. Socioeconomic effects include: the public's response to rising sea level, flood insurance costs, impact on tax base, sources of compensation for losses, legislation, government versus personal responsibility for costs, the decision making processes, emergency planning and responses, identification of future problems, water rights, and the financial resources needed to respond to the rising sea. Finally, it will be necessary to re-map and survey coastal areas and to obtain new bathymetry for the near offshore.

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[1] Although the information in this report has been funded wholly or partly by the U.S. Environmental Protection Agency under Contract No. CR-814577-01-0, it does not necessarily reflect the Agency's views, and no official endorsement should be inferred from it.

Responses and response strategies developed when confronted with sea level rise can include some or all of the following: constructing dikes, bulkheads, sea walls, revetments, groins, beach nourishment, construction of offshore breakwaters, storm surge barriers, dikes and polders. All of these represent an effort to resist the landward advance of the sea. In addition, there is always the alternative of abandoning some areas and structures or relocating structures on higher ground.

In the present study, the effects of sea level rise at six index sites in the United States were evaluated. The index sites were: the metropolitan New York City area; the Long Beach Island, New Jersey, area; the Corpus Christi, Texas, area; the Dividing Creek, New Jersey, area (a sparsely developed area); the south San Francisco Bay, California, area; and the Miami/Miami Beach, Florida, area. Using shoreline length, ground elevation distributions, and degree of development data, the six sites were evaluated in terms of the type of response judged to be most appropriate. The cost of responding to sea level rise was determined based on certain consistent assumptions. The response strategies can be categorized as follows:

1. Abandon those low-lying areas with little development and having a limited economic base.

2. Raise dwellings and other structures where appropriate.

3. Move isolated, structurally sound dwellings and other structures to new locations at higher elevation.

4. Surround low-lying economically developed areas with a dike; install a seawater seepage control system, an interior drainage system, and storage and pumping facilities to maintain drainage.

Costs for each of the above alternatives were developed by establishing unit costs for each element of a response strategy and then applying those costs to an assumption as to how each individual index site might respond to sea level rise. For example, in sparsely developed areas, isolated structures identified on United States Geological Survey (USGS) quadrangle maps were counted, and the cost of moving some fraction of them was estimated. (Because much of the data on building locations on the USGS quads is outdated, the number of buildings obtained from the quads was interpreted as only an indicator of the number of buildings present.) The cost to construct a dike around isolated communities and to provide an interior drainage system was estimated for areas with a reasonable level of economic development. The cost of raising and/or replacing roads that would connect such isolated areas with high land was also estimated. The cost of raising existing bulkheads and the cost of providing new bulkheads was estimated for those areas where such a response was believed appropriate. (The total cost of raising bulkheads cannot be allocated against sea level rise, since most bulkheads have a relatively short lifetime and need to be replaced periodically. Thus an accelerated sea level rise will result in a shorter lifetime and more frequent replacement. Such costs can be significantly reduced if sea level rise is anticipated in the initial design.)

The cost of responding to sea level rise for the total U.S. shoreline was determined by extrapolating costs for the six index sites to the rest of the U.S. coast. Costs at the six index sites were correlated with topographic and economic development factors, and then digitized topographic data obtained from USGS quad sheets were used to extrapolate costs to 78 additional sites around the U.S. shoreline. The extrapolation techniques make use of information on shoreline lengths, the distribution of land elevations, and the level of development.

CHAPTER 2

SEA LEVEL RISE SCENARIO

The sea level rise scenario assumed for the present study is summarized by Titus (this volume). The assumption is that by the year 2100, sea level will be 2 meters (6.5 feet) above the level it would have attained had it continued to rise at its local historical rate. Thus, the historical rate is extrapolated to the year 2100, and an additional 2 meters are added. The historical rate of rise is assumed to continue linearly, while the superposed 2-meter rise is assumed to increase parabolically. The general equation is given by,

$$RSL(t) = L(t) + 0.0012\ t + 0.0001434\ t^2 \qquad (1)$$

in which RSL(t) is the relative sea level, L(t) is a local sea level factor that includes the deviation of the local historical rate from the global rate (a local rate of rise based on historical tide gage records), and it is the number of years beyond the 1986 base year. For example, the rate of sea level rise in the Long Beach Island, New Jersey, area has been about 40 cm/100 years or 0.004 m/yr (Lyles et al., 1987); thus, the function $L(t) + 0.0012\ t = 0.004\ t$ and equation (1) for Long Beach Island becomes,

$$RSL(t) = 0.004\ t + 0.0001434\ t^2 \qquad (2)$$

Some of the analyses in the present study are not sensitive enough for the precise rate of sea level rise to become a factor in determining costs or for determining when certain actions in response to sea level rise will be triggered; however, for some detailed analyses the rates do enter into the cost calculations. For example, several alternatives were evaluated for Long Beach Island where the timing of certain actions depends on the stage of local sea level. On the other hand, several of the analyses simply assume that actions will be taken in response to sea level rise but the time when those actions are taken is not specified.

CHAPTER 3

INDEX SITE CONCEPT

To determine the cost of constructing dikes and other facilities to protect areas from inundation and from storm surge and wave damage, six index sites were selected for detailed study and used to develop correlations between data from those sites and data from other coastal sites around the continental U.S. The six sites were chosen to be a representative sample of the various types of coastal topography and development present in the U.S. with emphasis on developed areas where it is certain that some action to counter sea level rise will have to be taken. The sites were selected from among those being analyzed by Park et al. (this volume). The sites included: a) sections of New York City and its environs; b) Long Beach Island, New Jersey; c) Dividing Creek, New Jersey; d) Miami and Miami Beach, Florida; e) Corpus Christi, Texas; and f) portions of California's south San Francisco Bay area. The boundaries of the specific areas studied were selected to correspond with areas covered by USGS quad sheets. The sites, the USGS quads analyzed, and their dates of latest revision are given in Table 1. In addition, a portion of one of these index sites, Long Beach Island, New Jersey, was singled out for a more in-depth analysis.

Three scenarios of a coastal community's response to sea level rise were evaluated for Long Beach Island. They included: a) moving the island landward by reclaiming land on the bay side of the barrier while allowing the ocean side to recede in response to erosion caused by higher sea levels; b) artificially raising the island's elevation in conjunction with moving the island landward; and c) constructing dikes around the island and installing an interior drainage system to handle both storm drainage and seawater seepage beneath the dike system. Under the first two scenarios, houses would be moved to newly reclaimed land or raised in response to raising the island. In the third scenario, the island would have a protective dike built around it and the houses would be left in place.

TOPOGRAPHIC AND SHORELINE LENGTH ANALYSES

Topography at the six index sites was analyzed using the USGS quad sheets to obtain basic ground elevation and shoreline length data. Specifically, the shoreline length was measured using a rolling map-measure while areas enclosed within various elevation contours were planimetered. As a result, the total shoreline length was determined for each quad sheet along with that portion of the shoreline that is presently protected by bulkheads. The area between various contours on the quad sheets was planimetered and the topographic characteristics determined by plotting the distribution of ground elevations. For example, the distribution of elevations for the New York City metropolitan area is given in Figure 1. In general, each site has a characteristic topographic distribution that determines its vulnerability to inundation by a rise in sea level.

New York Metropolitan Area, New York and New Jersey

The New York City metropolitan area is an intensively developed urban area characterized by heavily populated residential areas as well as large-scale commercial and industrial development. It is perhaps the most intensely developed metropolitan area of the United States. It also has a long, heavily developed shoreline, most of which is already protected by structures such as bulkheads or revetments. Major metropolitan subdivisions include: Manhattan, Brooklyn, Queens, The Bronx, and Staten Island, New York; and Elizabeth, Jersey City, Union City, and Linden, New Jersey. In general, 26% of the land on the quads lies below the +5 foot contour while 52% lies below the +10 foot National Geodetic Vertical Datum (NGVD) elevation. (NGVD is sometimes referred to as the mean sea level datum of 1929.) On the other hand, there are few undisturbed wetlands on the quads (except for the wetlands along the west bank of the Hackensack River), so that erosion will be more of a concern than simple inundation. The distribution of land elevations planimetered from the quads is summarized in Table 2 and shown in Figure 1. (The contour interval of the seven USGS quads that cover the study area is 10 feet so that the distribution of land elevations below the 10-foot contour cannot be determined

TABLE 1 INDEX SITES AND CORRESPONDING USGS QUAD SHEETS

Nominal Index Site	USGS Quad Sheets	Original Date	Photo-Revision
New York, NY			
	Weehawken, NJ	1967	1981
	Central Park, NY	1966	1979
	Elizabeth, NJ	1967	1981
	Jersey City, NJ	1967	1981
	Brooklyn, NY	1967	1979
	Arthur Kill, NJ	1966	1981
	The Narrows, NY	1966	1981
* Long Beach Island, NJ			
	Barnegat Light, NJ	1953	1972
	Long Beach NE, NJ	1951	1972-77
	Ship Bottom, NJ	1952	1972
	Tuckerton, NJ	1952	1972
	Beach Haven, NJ	1951	1972-77
Dividing Creek, NJ			
	Dividing Creek, NJ	1956	1972
	Cedarville, NJ	1956	1972-82
	Port Norris, NJ	1956	1972
	Fortescue, NJ	1956	1972
Miami, FL			
	North Miami, FL	1962	1969-72
	Miami, FL	1962	1969
Corpus Christi, TX			
	Oso Creek NE, TX	1968	1975
	Oso Creek NW, TX	1968	1975
	Port Ingleside, TX	1968	1975
	Crane Islands NW, TX	1968	1975
	Portland, TX	1968	-
	Corpus Christi, TX	1968	1975
San Francisco, CA			
	Palo Alto, CA	1961	1968-73
	Mountain View, CA	1961	1981
	Redwood Point, CA	1959	1980
	Newark, CA	1959	1980

* Index site selected for more detailed analysis of alternatives.

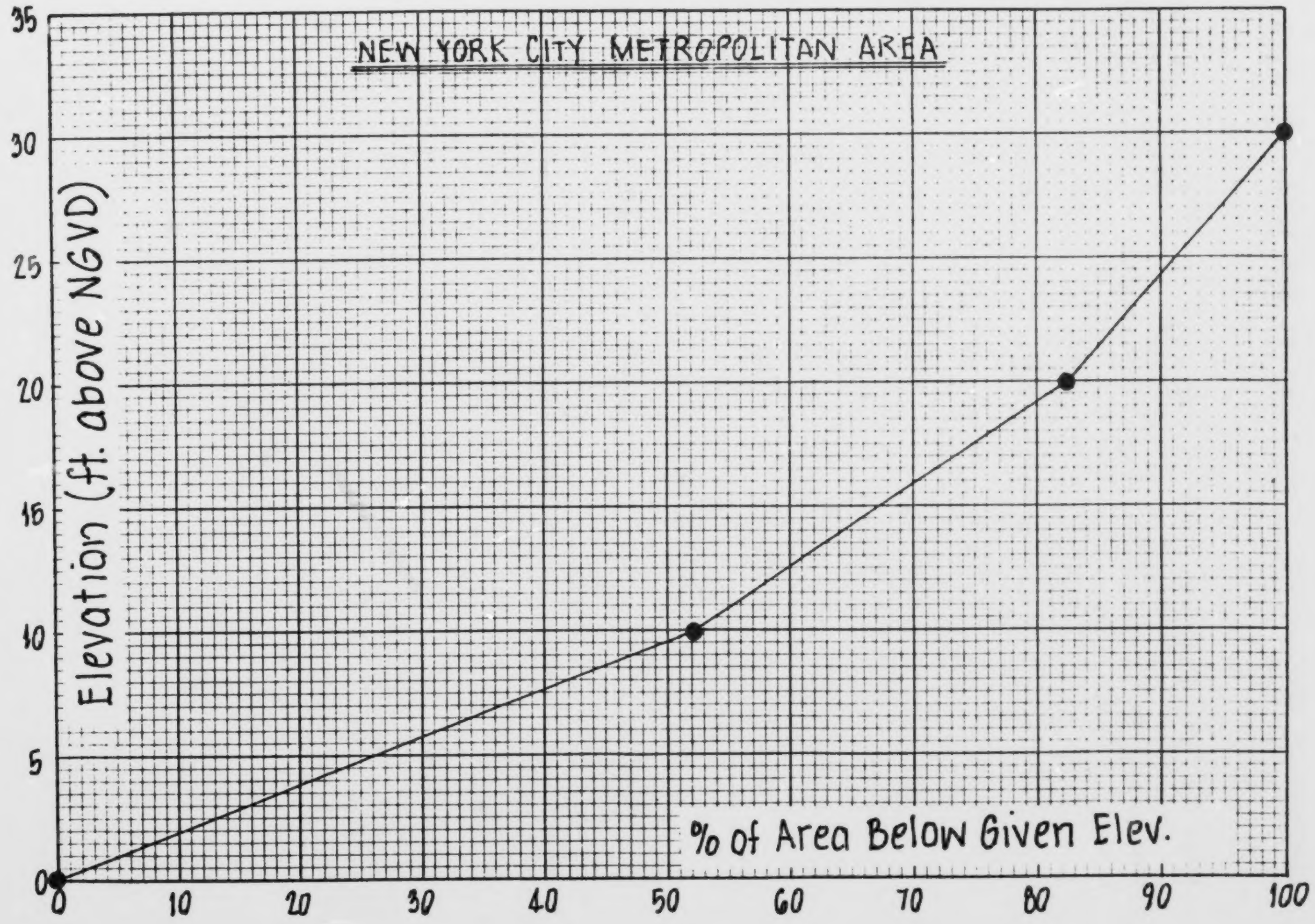


Figure 1 Distribution of Ground Elevations - New York City Metropolitan Area.

TABLE 2 SUMMARY OF TOPOGRAPHIC CONDITIONS AT NEW YORK, NEW YORK

USGS Quad	Area (sq mi) Between Given Elevations (ft) 0<Z<10 *	10<Z<20	20<Z<30	Total Area	Wetlands Area
Weehawken	30.60	4.41	1.42	36.43	2.30
Arthur Kill	15.35	9.17	5.04	29.56	
Brooklyn	2.72	8.60	6.33	17.65	
The Narrows	2.94	2.15	1.65	6.74	
Jersey City	12.54	6.71	2.76	22.01	
Elizabeth	11.60	7.92	4.21	23.72	
Central Park	2.39	5.60	4.68	12.67	
OVERALL TOTALS					
TOTAL	78.14	44.55	26.09	148.77	2.30
% OF TOTAL	52.5	30.0	17.5		
CUM %	52.5	82.5	100.0		

* Datum is NGVD.

from the quads. The digitized topographic data allowed a better resolution of elevations than the present analysis.) The USGS quads that cover the present study area include: Weehawken, Arthur Kill, Brooklyn, The Narrows, Jersey City, Elizabeth, and Central Park. Major bodies of water include the Hudson, Hackensack, East, Arthur Kill, and Kill van Kull Rivers; Newark Bay, the Verazzano Narrows, Upper Bay, Lower Bay, and the Raritan Bay. The shoreline lengths are given in Table 3. Table 3a is a partial summary of shoreline lengths by region. Table 3a does not include the total shoreline shown on all seven quads. Of the 220 miles of shoreline included in the study area, 155 miles (70%) are bulkheaded.

Long Beach Island Area, New Jersey

Long Beach Island, New Jersey, is a sandy barrier island near the center of New Jersey's Atlantic Ocean shoreline. The island is located approximately 45 miles south of Sandy Hook and 55 miles north of Cape May and is bounded by Barnegat Inlet on the north and Beach Haven and Little Egg Harbor Inlets on the south. The island is about 23 miles long. The mainland behind the barrier island is bordered by extensive wetlands. There are also numerous wetlands islands in the bays behind the barrier island. The five USGS quads that cover the study area are: Barnegat Light, Long Beach NE, Ship Bottom, Tuckerton, and Beach Haven. The distribution of elevations on the five USGS quads is given in Table 4 and in Figure 2. Generally, the barrier island is at about the +3.5-foot NGVD elevation with only a few scattered areas of high dunes where the elevation exceeds +10 feet. (The demarcation between wetlands and fast land on the quads was assumed to be the +3.5-foot NGVD contour.) Large areas of the mainland are below the +3.5-foot NGVD elevation, however. The overall topographic summary indicates that almost 50% of the land area is below +3.5 feet NGVD; about 80% is below +10 feet, and 93% is below 20 feet.

Shoreline lengths are summarized in Table 5. Long Beach Island's shoreline is about 55 miles long. About 23 miles front the Atlantic Ocean while the remainder is bay shoreline. The shoreline defined by the interface between the mainland and wetlands is about 33 miles long, while the outer wetlands shoreline is about 55 miles long.

Long Beach Island was selected for detailed analysis to investigate the cost of several alternative responses to sea level rise. This analysis is presented in a later section. A more detailed description of Long Beach Island is also presented there.

Dividing Creek, New Jersey

The Dividing Creek, New Jersey, area is a sparsely developed area bordering the Delaware Bay near where the Maurice River discharges into the bay. The area considered in the present study is covered by four USGS Quads and is mostly composed of wetlands having an elevation below +5 feet NGVD; much of it is state-owned hunting lands. The USGS quads covering the area are: Dividing Creek, Cedarville, Port Norris, and Fortescue. The region is criss-crossed by small streams and drainage channels. There are several small communities in the area. They include the bayside towns of Fortescue and Gandys Beach, the town of Dividing Creek on the fast land behind the wetlands, and the towns of Laurel Lake and Cedarville on the Maurice River and Cedar Creek, respectively. Laurel Lake and Cedarville are mostly above +10 feet NGVD, while significant portions of the remaining towns are below +10 feet elevation. The distribution of land elevations obtained by planimetering the USGS quads is summarized in Table 6 and shown in Figure 3. About half of the land area is below the +5-foot contour (defined here as wetlands area), while fully 92% of the land area is below the 20-foot contour. The shoreline lengths on the four quads are summarized in Table 7. The shoreline length is about 97 miles and is defined here as the interface between the wetlands and Delaware Bay. Dividing Creek is believed to be typical of much of the undeveloped U.S. coastlines such as areas on the mainland behind barrier islands. For example, the mainland areas in North Carolina in sounds and bays behind the Outer Banks might be characterized by the level of development and wetlands of the Dividing Creek area.

TABLE 3 SUMMARY OF SHORELINE LENGTHS - NEW YORK, NEW YORK

USGS Quad	Shoreline Length			Wetlands Shoreline (mi)
	Bulk. (mi)	Unbulk. (mi)	Total (mi)	
MANHATTAN ISLAND				
Weehawken	0.89	0.15	1.04	
Central Park	13.79	5.59	19.39	
Jersey City	4.32	0.15	4.47	
Brooklyn	4.18	0	4.18	
SUB TOTAL	23.19	5.89	29.08	
STATEN ISLAND				
Jersey City	8.13	0.52	8.65	
Elizabeth	4.18	1.57	5.74	2.09 *
Arthur Kill	4.03	17.89	21.92	
The Narrows	1.49	6.26	7.75	
SUB TOTAL	17.82	26.25	44.07	2.09 *
ELIZABETH				
Elizabeth	6.93	7.46	14.39	
SUB TOTAL	6.93	7.46	14.39	
JERSEY - UNION CITY				
Weehawken	20.43	0	20.43	27.89 *
Jersey City	2.23	1.49	3.72	
Elizabeth	10.89	1.49	12.38	
SUB TOTAL	33.55	2.98	36.53	27.89 *

* Wetlands shoreline length not included in total shoreline length.

TABLE 3 (cont.) SUMMARY OF SHORELINE LENGTHS - NEW YORK, NEW YORK

USGS Quad	Shoreline Length Bulk. (mi)	Unbulk. (mi)	Total (mi)	Wetlands Shoreline (mi)
	BRONX - QUEENS - BROOKLYN			
Weehawken	16.40	11.93	28.33	
Brooklyn	10.73	0	10.73	
Jersey City	43.11	9.09	52.20	
The Narrows	4.10	1.27	5.37	
SUB TOTAL	74.34	22.29	96.63	
TOTAL	155.83	64.87	220.70	29.98 *

TABLE 3A SUMMARY OF SHORELINE LENGTHS BY REGION

Region	Shoreline Length Bulk. (mi)	Unbulk. (mi)	Total (mi)	Wetlands Shoreline (mi)
Jersey City	45.56	17.15	62.71	27.89 *
Brooklyn	36.98	1.71	38.70	
Bronx	6.70	4.29	11.63	
Queens	4.76	2.98	7.75	
Elizabeth	22.89	3.88	26.77	
Governors Is.	2.16	0	2.16	
TOTAL	119.05	30.01	149.06	27.89 *

* Wetlands shoreline length not included in total shoreline length.

TABLE 4 SUMMARY OF TOPOGRAPHIC CONDITIONS ON LONG BEACH ISLAND AND ADJACENT MAINLAND, NEW JERSEY

USGS Quad	Area (sq mi) Between Given Elevations (ft)					Total Area	Wetlands Area
	$0<Z<3.5$	$3.5<Z<10$	$10<Z<20$	$20<Z<30$	$30<Z<40$		
			LONG BEACH ISLAND				
Barnegat Light	0.014	0.589	0.037	0.021	0	0.661	0.234
Long Beach NE	0.023	0.476	0.101	0.015	0	0.615	0.021
Ship Bottom	0.075	2.580	0.188	0.023	0	2.866	1.212*
Tuckerton	0.096	0.963	0.078	0	0	1.137	2.562*
Beach Haven	0.216	1.645	0.273	0.005	0	2.138	0.216
TOTAL	0.423	6.254	0.676	0.063	0	7.417	4.244*
% OF TOTAL	5.7	84.4	9.1	0.8		100.0	
CUM %	5.7	90.1	99.2	100.0			
			ISLAND BEACH STATE PARK				
Barnegat Light	1.452	0.373	0.538	0.116	0.020	2.500	1.452
TOTAL	1.452	0.373	0.538	0.116	0.020	2.500	1.452
% OF TOTAL	58.0	15.0	21.6	4.6	0.8	100.0	
CUM %	58.0	73.0	94.6	99.2	100.0		
			MAINLAND BEHIND LONG BEACH ISLAND				
Ship Bottom	7.723	5.002	3.125	1.012	0	16.862	7.724
Tuckerton	12.950	2.282	1.819	2.066	0	19.117	12.950
TOTAL	20.673	7.284	4.944	3.078	0	35.979	20.674
% OF TOTAL	57.5	20.2	13.7	8.6	0	100.0	
CUM %	57.5	77.7	91.4	100.0	100.0	100.0	
			OVERALL TOTALS				
TOTALS	22.55	13.91	6.16	3.26	0.02	45.90	
% OF TOTAL	49.1	30.3	13.4	7.1	-	100.0	
CUM %	49.1	79.4	92.8	99.9	100.0		

* Includes wetlands areas on islands in bay behind Long Beach Island.

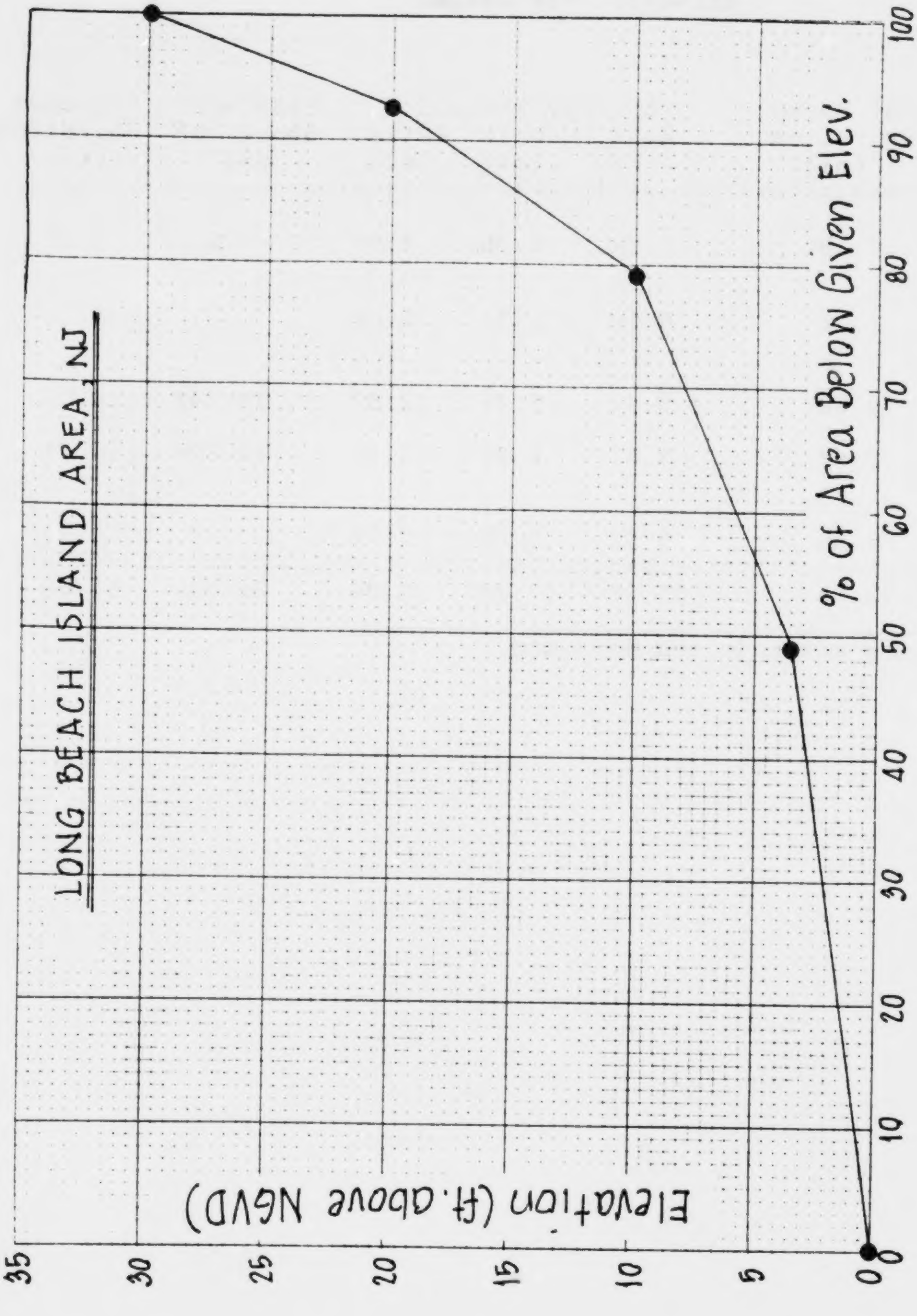


Figure 2 Distribution of Ground Elevations - Long Beach Island, NJ Area.

TABLE 5 SUMMARY OF SHORELINE LENGTHS AT LONG BEACH ISLAND AND ADJACENT MAINLAND, NEW JERSEY

USGS Quad	LBI Ocean Shoreline (mi)	LBI Bay Shoreline			Mainland Shoreline (mi)	Wetlands Shoreline (mi)
		Bulk. (mi)	Unbulk. (mi)	Total (mi)		
Barnegat Light	1.19	0.74	1.86	2.60	0	4.32
Long Beach NE	2.24	0.30	1.79	2.09	0	0.60
Ship Bottom	9.39	6.41	6.26	12.67	18.24*	26.60
Tuckerton	3.87	2.61	4.69	7.30	14.60*	18.17
Beach Haven	6.26	5.02	2.68	7.70	0	4.79
TOTAL (mi)	22.95	15.08	17.28	32.36	32.84	54.48

* Boundary between wetlands and mainland.

TABLE 6 SUMMARY OF TOPOGRAPHIC CONDITIONS IN DIVIDING CREEK, NEW JERSEY

USGS Quad	Area (sq mi) Between Given Elevations (ft) 0<Z<5	5<Z<10	10<Z<20	20<Z<30	30<Z<40	Total Area	Wetlands Area
Dividing Creek	6.66	10.56	9.57	4.47	-	31.25	6.66
Cedarville	15.43	11.95	4.70	2.29	-	34.36	15.43
Port Norris	15.69	1.88	0.42	0.02	-	18.01	15.69
Fortescue	10.41	-	-	-	-	10.41	10.41

OVERALL TOTALS

	0<Z<5	5<Z<10	10<Z<20	20<Z<30	30<Z<40	Total Area	Wetlands Area
TOTAL	48.19	24.39	14.69	6.79	-	94.05	48.19
% OF TOTAL	51.23	25.93	15.62	7.21	-	100.0	
CUM %	51.23	77.16	92.78	100.00			

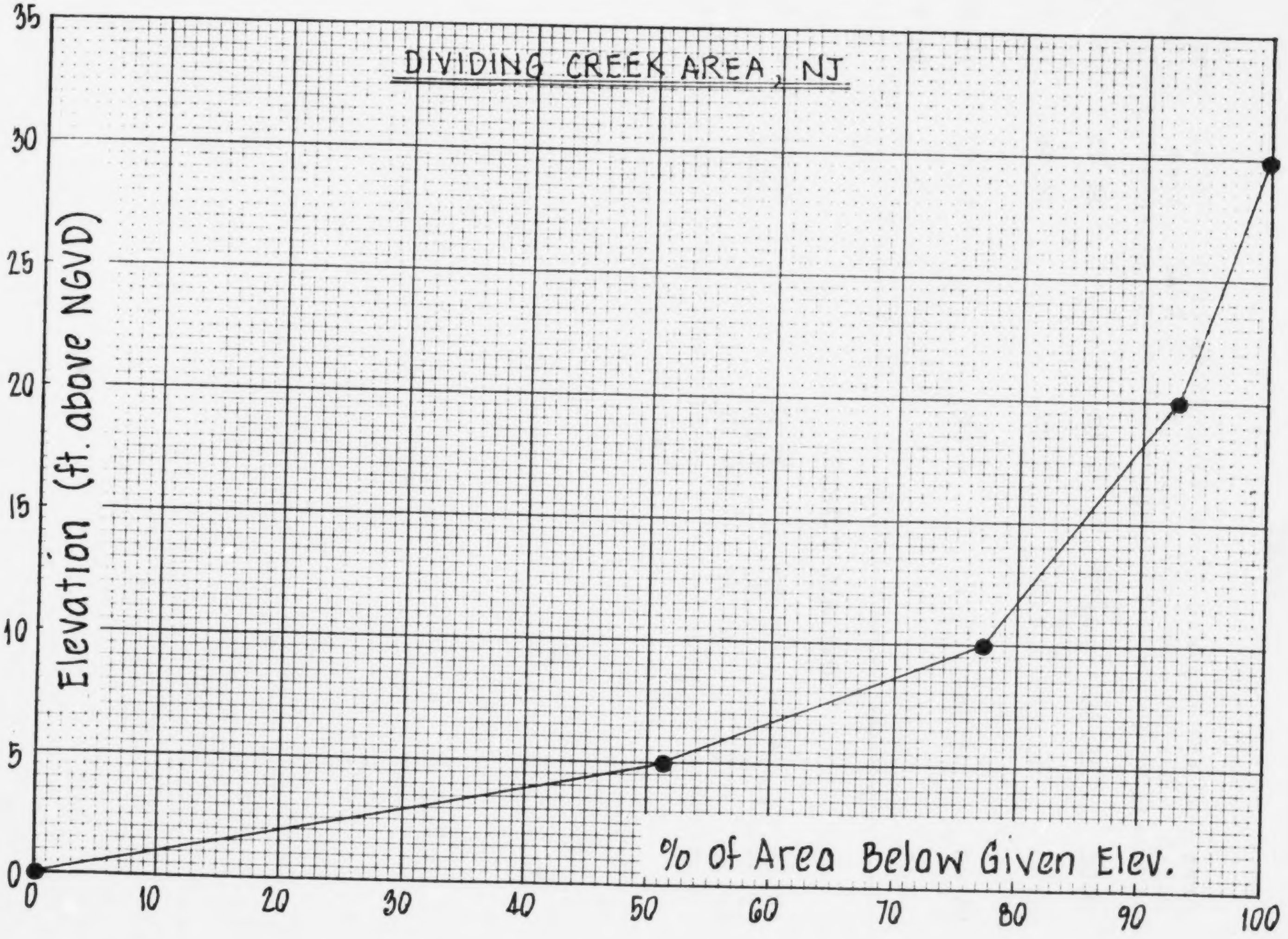


Figure 3 Distribution of Ground Elevations - Dividing Creek, NJ Area.

TABLE 7 SUMMARY OF SHORELINE LENGTHS AT DIVIDING CREEK, NEW JERSEY

USGS Quad	Delaware Bay * Shoreline (mi)
Dividing Creek	17.88
Cedarville	51.07
Port Norris	19.22
Fortescue	8.79
TOTAL (mi)	96.96

* Boundary between wetlands and Delaware Bay

Miami and Miami Beach Area, Florida

The Miami/Miami Beach, Florida, area is covered by two USGS quads: Miami and North Miami. The area is heavily developed, both commercially and residentially. Miami Beach is primarily a resort area while Miami itself is a major metropolitan area. Major municipalities include the City of Miami itself, North Miami, Miami Shores, and North Miami Beach on the mainland, and Miami Beach on the barrier island. There are also many smaller political subdivisions. The land is generally low in elevation as shown in Table 8. The distribution of land elevations is shown in Figure 4 and summarized in Table 8. While only 16% of the land is below +5-foot NGVD elevation, 52% is between +5 and +10 feet so that 69% is below +10 feet and 98% is below +15 feet in elevation. There is virtually no land above the +20-foot elevation. In addition, most of the low-lying land is heavily developed and very little of it is undeveloped wetlands. As a result of the low-lying topography, most of the shoreline has been bulkheaded. Shoreline lengths are summarized in Table 9. Of the 125 miles of shoreline on the USGS quads, more than 100 miles or 80% are bulkheaded. The shorelines in Table 9 are classified as either ocean or bay shoreline. The major bodies of water are the Atlantic Ocean fronting the barrier island, and Miami Beach and Biscayne Bay, the bay between the Miami Beach barrier island and the mainland. Numerous manmade or man-improved islands are located in Biscayne Bay. Many of them support residential development or they serve to support causeways that connect the barrier island with the mainland. Most of these small islands' shorelines are completely bulkheaded.

Corpus Christi Area, Texas

Corpus Christi, Texas, is located on the Gulf of Mexico about 150 miles north of the U.S.-Mexican border. The area is developed around the major city of Corpus Christi and several smaller municipalities such as Portland and Ingleside. The towns are located on Corpus Christi Bay and are sheltered from the Gulf of Mexico by Mustang Island and Padre Island, two undeveloped barrier islands. Portions of the undeveloped barrier islands are included in the present analysis. The area under study is covered by six USGS quads: Corpus Christi, Crane Island NW, Oso Creek NE, Oso Creek NW, Port Ingleside, and Portland. The distribution of land elevations in the Corpus Christi area is given in Figure 5 and summarized in Table 10. In general, little land is below the +5-foot contour (only 9%), while all of it is below the 30-foot contour. The land elevation distribution at Corpus Christi is somewhat unique among the index sites, since the function is approximately linear suggesting a very steep shoreline in an average sense.

The shoreline length and its distribution among the six quads is given in Table 11. Most of the 189-mile-long shoreline is unbulkheaded.

San Francisco Bay Area, California

The portion of the south San Francisco Bay Area considered in the present study is covered by the following four USGS quads: Redwood Point, Newark, Palo Alto, and Mountain View. The area covered is the shallow, southernmost portion of San Francisco Bay. The major metropolitan areas in the area are Hayward, Newark, and Fremont on the east side of the bay, and Palo Alto, Redwood City, Sunnyvale, Mountain View, and Menlo Park on the west side of the bay. Most of the residential areas associated with these towns are at sufficiently high elevation to not be significantly affected by sea level rise of the magnitude under consideration here; however, the low-lying areas surrounding the bay itself are vulnerable. Generally, terrain in the San Francisco area is quite hilly except for the low-lying areas adjacent to the San Francisco Bay. Most of the bay shoreline in this area is covered by salt evaporators: portions of the bay separated from the main bay by levees and used to commercially extract salt from bay water through natural evaporation. The bay is thus subdivided by the levees. Redwood Creek and Steinberger Slough drain into the bay in this area. The distribution of elevations is given in Figure 6 and summarized in Table 12 for that portion of the area below the +30-foot contour. Because of the evaporators, 59% of the land lower than +30 feet is below +5 feet NGVD elevation. Shoreline lengths are summarized in Table 13. Two lengths are given in the table: the length along the outermost levees that separate the evaporators from the bay, and the shoreline length behind the evaporators, i.e., the shoreline between the evaporators and fast land. This latter shoreline nearly coincides with the +5-foot contour.

TABLE 8 SUMMARY OF TOPGRAPHIC CONDITIONS AT MIAMI AND MIAMI BEACH, FLORIDA

USGS Quad	Area (sq mi) Between Given Elevations (ft)					Total Area
	$0<Z<5$	$5<Z<10$	$10<Z<15$	$15<Z<20$	$20<Z$	
MIAMI BEACH						
North Miami	1.72	1.35	0.33	0.03	0	3.43
Miami	4.38	2.22	0.08	0.02	0	6.70
TOTAL	6.10	3.57	0.41	0.05	0	10.13
% OF TOTAL	60.2	35.2	4.0	0.5		100.0
CUM %	60.2	95.4	99.4	100.0		
MIAMI						
North Miami	12.65	36.36	13.01	0.05	0	62.08
Miami	3.85	15.95	15.32	1.79	0	36.92
TOTAL	16.50	52.31	28.33	1.84	0	99.00
% OF TOTAL	16.7	52.8	28.6	1.9		100.0
CUM %	16.7	69.4	98.1	100.0		
OVERALL TOTALS						
TOTAL	22.60	55.88	28.74	1.89		109.13
% OF TOTAL	20.7	51.2	26.3	1.7		100.0
CUM %	20.7	71.9	98.2	100.0		

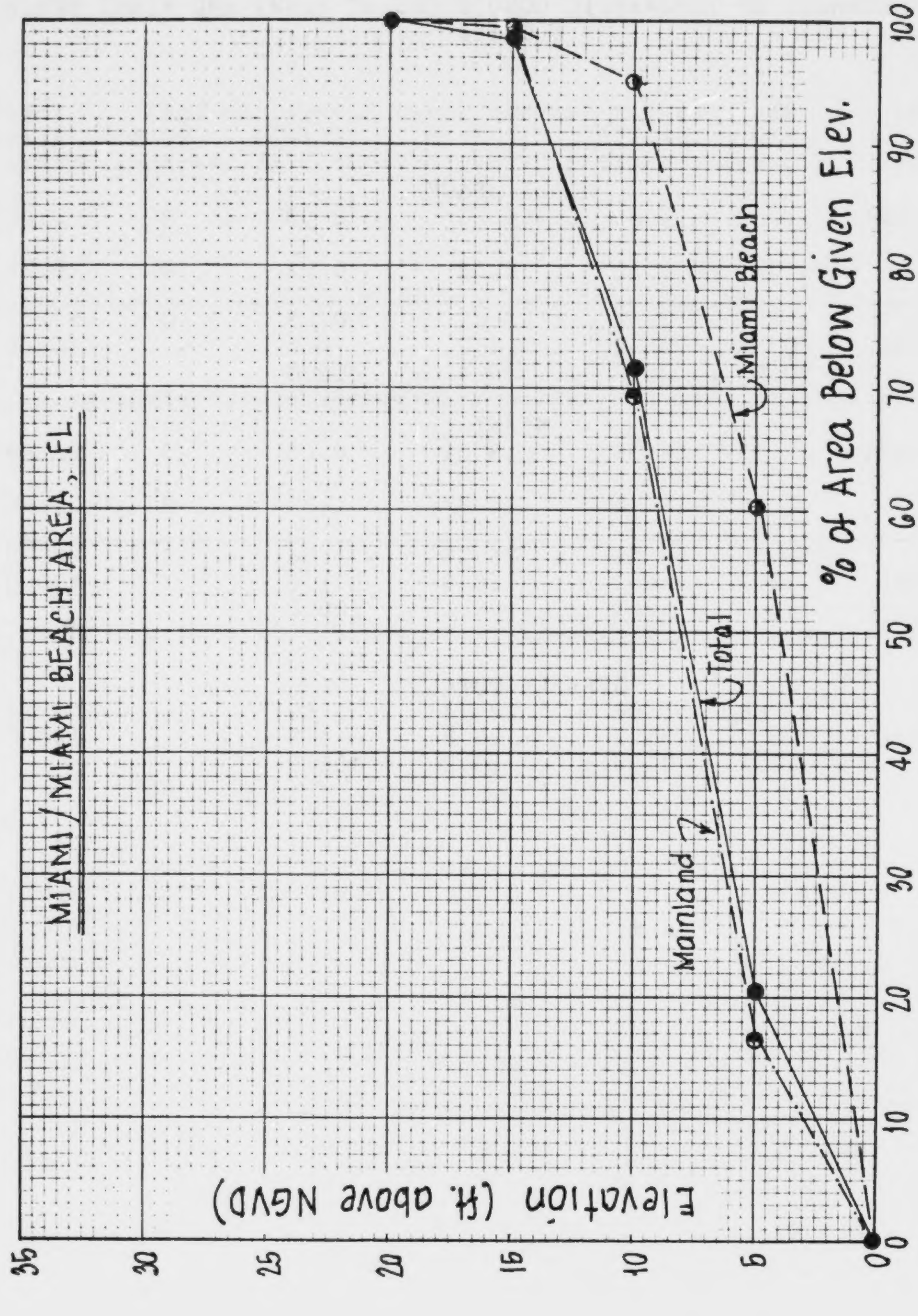


Figure 4 Distribution of Ground Elevations - Miami/Miami Beach, FL Area.

TABLE 9 SUMMARY OF SHORELINE LENGTHS AT MIAMI BEACH, FLORIDA

USGS Quad	Ocean Shoreline (mi)	Bay Shoreline *			Mainland Shoreline		
		Bulk. (mi)	Unbulk. (mi)	Total (mi)	Bulk. (mi)	Unbulk. (mi)	Total (mi)
North Miami	8.49	15.93	2.98	18.91	6.44	3.84	10.28
Miami	7.75	68.85	16.08	84.93	10.21	0.82	11.03
TOTAL (mi)	16.24	84.78	19.06	103.83	16.65	4.66	21.31

* Includes shoreline of islands in bay between Miami and Miami Beach

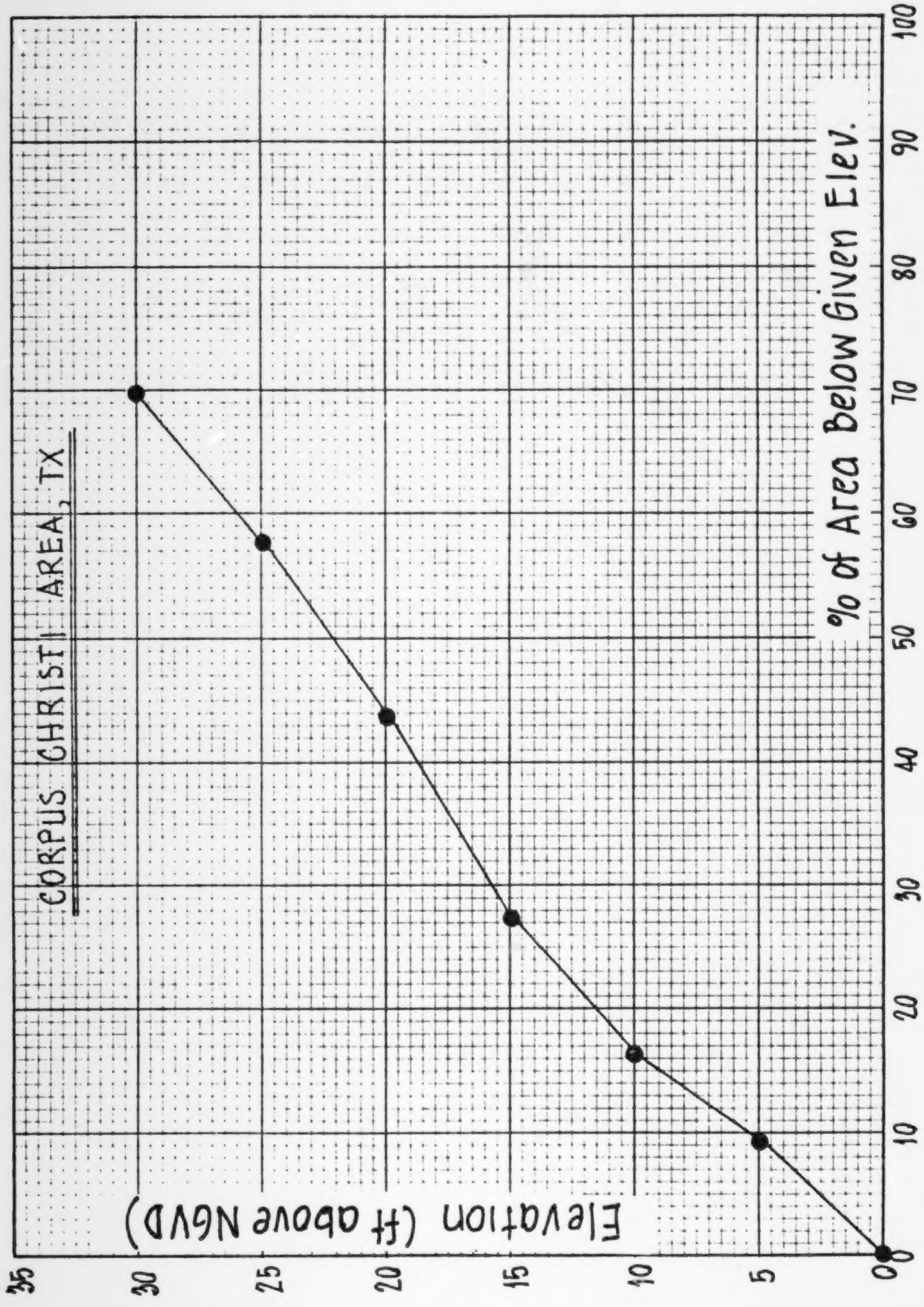


Figure 5 Distribution of Ground Elevations - Corpus Christi, TX Area.

TABLE 10 SUMMARY OF TOPOGRAPHIC CONDITIONS AT CORPUS CHRISTI, TEXAS

USGS Quad	Area (sq mi) Between Given Elevations (ft)							Total Area
	0<Z<5	5<Z<10	10<Z<15	15<Z<20	20<Z<25	25<Z<30	30<Z	
Oso Creek NE								
Encinal	1.22	1.65	4.66	7.50	1.19	0.63	-	16.85
Mainland	0.59	0.09	5.03	6.92	3.29	0.01	-	16.73
Ward Is.	0.08	0.09	0.20	0.02	-	-	-	0.39
JFK Caus.	0.04	0.02	-	-	-	-	-	0.06
TOTALS	1.93	2.66	9.89	14.14	4.48	0.64	-	34.03
% OF TOTAL	5.7	7.8	29.1	42.4	13.2	1.9		
CUM %	5.7	13.5	42.5	85.0	98.1	100.0		
Oso Creek NW								
Below HW2444 Bridge	0.90	1.07	2.67	6.79	13.60	15.07	22.05	62.15
TOTALS	0.90	1.07	2.67	6.79	13.60	15.07	22.05	62.15
% OF TOTAL	1.4	1.7	4.3	10.9	21.9	24.2	35.5	
CUM %	1.4	3.1	7.4	18.3	40.2	64.4	100.0	
Port Ingleside								
Mainland	0.49	0.86	1.97	3.75	2.34	1.08	0.87	11.36
Undev. Is.	1.87	0.71	0.20	0.05	0.03	0.02	-	2.87
TOTALS	2.36	1.57	2.17	3.80	2.37	1.10	0.87	14.24
% OF TOTAL	16.6	11.0	15.2	26.7	16.6	7.7	6.1	
CUM %	16.6	27.6	42.8	69.5	86.1	93.8	100.0	
Crane Islands NW								
Mustang Is	5.88	3.21	1.07	0.53	-	-	-	10.69
Mainland	0.31	0.21	0.07	0.01	-	-	-	0.60
TOTALS	6.19	3.42	1.14	0.54				11.29
% OF TOTAL	54.8	30.3	10.1	4.8				
CUM %	54.8	85.1	95.2	100.0				
Portland	0.28	0.11	0.03	0.03	0.03	0.03	-	0.52
Corpus Christi	2.48	2.49	1.46	0.73	1.41	1.95	24.7	35.22
TOTALS	2.76	2.60	1.49	0.76	1.44	1.98	24.7	35.74
% OF TOTAL	7.7	7.3	4.2	2.1	4.0	5.5	69.1	
CUM %	7.7	15.0	19.2	21.3	25.3	30.8	100.0	

OVERALL TOTALS

TOTALS	14.14	11.32	17.36	26.03	21.89	18.79	47.62	157.15
% OF TOTAL	9.0	7.2	11.0	16.6	13.9	12.0	30.3	
CUM %	9.0	16.2	27.2	43.8	57.7	69.7	100.0	

TABLE 11 SUMMARY OF SHORELINE LENGTHS - CORPUS CHRIST AREA, TEXAS

USGS Quad	Shoreline Length		
	Bulk. (mi)	Unbulk. (mi)	Total (mi)
Corpus Christi	9.7	41.3	51.0
Crane Island NW	1.7	42.4	44.1
Oso Creek NE	7.8	36.2	44.0
Oso Creek NW	-	6.0	6.0 *
Port Ingleside	2.6	29.8	32.4
Portland	1.7	9.8	11.5
TOTALS	23.5	165.5	189.0

* Along Oso Creek

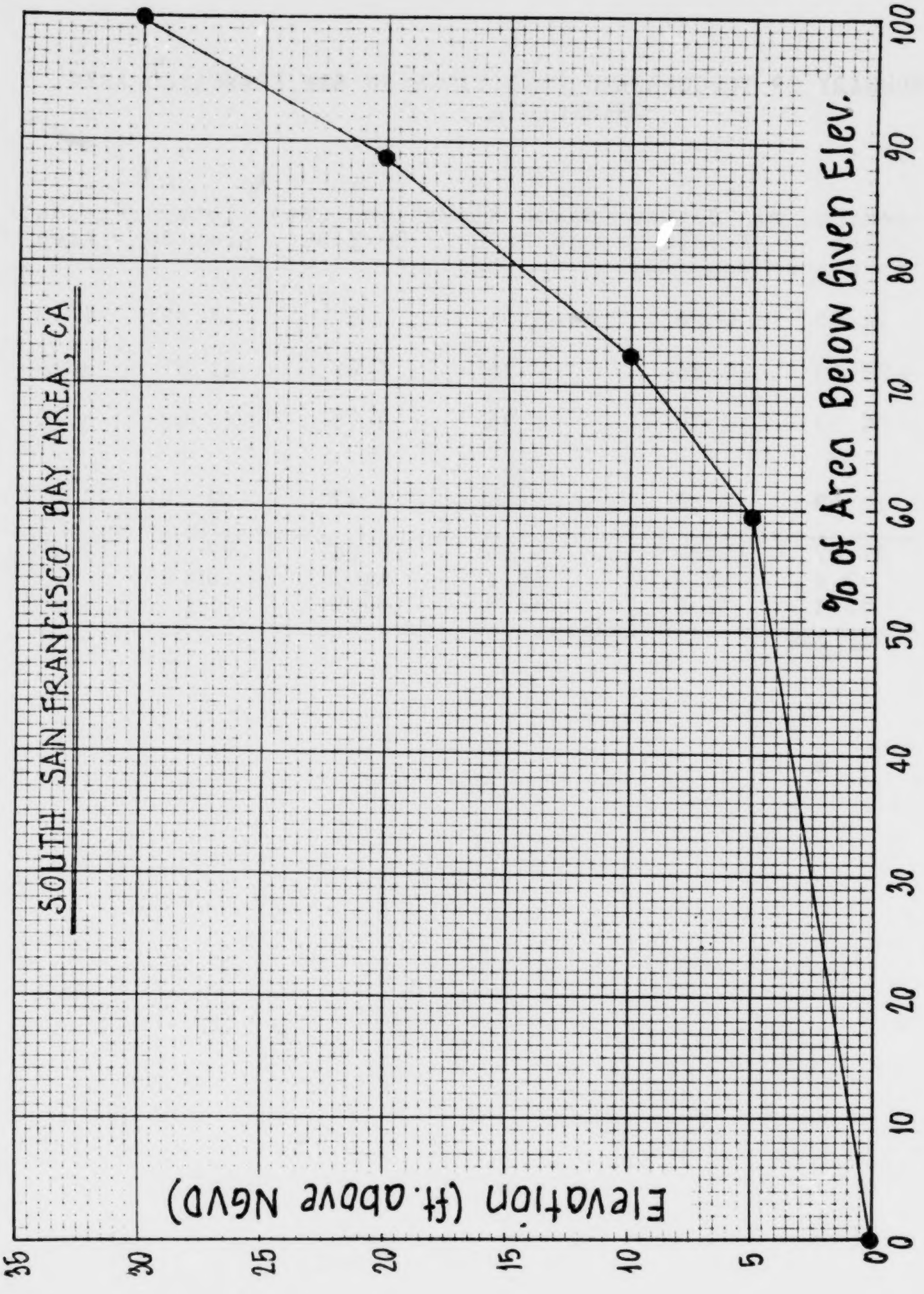


Figure 6 Distribution of Ground Elevations - South San Francisco Bay, CA Area.

TABLE 12 SUMMARY OF TOPOGRAPHIC CONDITIONS IN SAN FRANCISCO AREA, CALIFORNIA

USGS Quad	Area (sq mi) Between Given Elevations (ft) 0<Z<5	5<Z<10	10<Z<20	20<Z<30	Total Area<30	Wetlands Area
Redwood Point	14.65	0.26	0.01	0	14.92	4.28
Newark	22.10	7.34	7.75	4.62	41.81	3.19
Palo Alto	6.33	2.70	4.25	3.75	17.03	0.40
Mountain View	14.59	2.57	3.64	2.47	23.28	2.31
TOTAL	57.67	12.87	15.65	10.84	97.04	10.18
% OF TOTAL	59.4	13.3	16.1	11.2	100.0	
CUM %	59.4	72.7	88.8	100.0		

TABLE 13 SUMMARY OF SHORELINE LENGTHS - SAN FRANCISCO AREA, CALIFORNIA

USGS Quad	Inner Shoreline Length * (mi)	Outer Shoreline Length ** (mi)
Redwood Point	0.89	18.19
Newark	14.76	6.26
Palo Alto	8.35	0.89
Mountain View	13.00	17.00
TOTAL	37.00	42.35

* Shoreline between salt evaporators and mainland (approximately coincides with 5 foot contour.

** Shoreline between evaporators and San Francisco Bay.

CHAPTER 4

LONG BEACH ISLAND, NEW JERSEY - IN-DEPTH ANALYSIS

EVALUATION OF ALTERNATIVES

Long Beach Island, New Jersey, is a barrier island approximately 23 miles long, averaging between 1000 and 3200 feet wide. It comprises an area of about 7.4 square miles. It is bounded on the north by Barnegat Inlet and on the south by Beach Haven and Little Egg Inlets. The island shelters Little Egg Harbor and Manahawkin and Barnegat Bays from the Atlantic Ocean. The island is entirely developed with single-family houses except for the southern 3 miles, which is part of Brigantine National Wildlife Refuge. There are no high-rise condominiums and only one motel with as many as three stories. It is heavily populated by vacationers during the summer months but the population during the remainder of the year is relatively small. Access to the island is by a single bridge from Manahawkin on the mainland to the town of Ship Bottom near the middle of the island. Long Beach Island's ocean shoreline is protected by dunes along most of its entire length. The dune crests are at about +10 feet above NGVD with a few rising to +20 feet. The island's bay shoreline is about 32 miles long; about 15 miles of the bay shoreline is bulkheaded. See Table 5. The bay shoreline is dotted with small marinas and other boat launching and docking facilities. There is also a small amount of salt marsh along the bay shoreline comprising about 0.43 square miles or 5.7% of the island's area.

SHORELINE AND TOPOGRAPHIC CONDITIONS

Shoreline lengths along Long Beach Island and the adjacent mainland are summarized in Table 5, and topographic conditions are summarized in Table 4. These data are given for each of the USGS quad sheets analyzed. Long Beach Island is covered by five quads: Barnegat Light, Long Beach NE, Ship Bottom, Tuckerton, and Beach Haven. The Barnegat Light quad also covers the southern end of Island Beach State Park, the undeveloped barrier island just north of Long Beach Island, while the Ship Bottom and Tuckerton quads also cover a significant area of the mainland behind Long Beach Island. The distribution of elevations on Long Beach Island is given in Figure 7. About 6% of the island is below about 3.5 feet in elevation (NGVD); about 84% of the island is between 3.5 feet and 10 feet in elevation. Only 9% is above 10 feet, and less than 1% (a few scattered high dunes near the northern end of the island) is above 20 feet in elevation. The distribution of elevations on the mainland is significantly different. (See Figure 7 for the distribution of elevations on both the mainland and on the barrier island.) Of the mainland area below 40 feet in elevation, about 57% is below +3.5 feet NGVD. This area is defined as coastal wetlands on the USGS quads.

LEVEL OF DEVELOPMENT

The level of development on Long Beach Island was determined from an analysis of aerial photographs obtained from the New Jersey Department of Environmental Protection, Bureau of Coastal Engineering. Two sets of photographs, dated March 23, 1982, and March 30, 1984, were used to determine the number of buildings on the island and their location relative to the prevailing high-water shoreline. These data are summarized in Table 14. The distribution of houses with respect to the shoreline is plotted in Figure 8. The cumulative number of houses summed along the entire length of the island is plotted as a function of the distance measured landward across the island from the high water shoreline. Thus if the shoreline were to erode 500 feet from the ocean side, approximately 4,700 buildings on Long Beach Island would be affected. If the shoreline were to erode 1,000 feet, 9,800 buildings would be located seaward of the new shoreline. This relationship is nearly linear, indicating an almost uniform level of development across the island from its seaward side to its bayward side. It deviates from a linear relationship only for distances exceeding 1,000 feet because of the island's variable width. Thus the cumulative number of buildings drops off for distances greater than 1,000 feet with that distance measured from the existing high-water shoreline. The linear portion of the curve can be expressed by the equation:

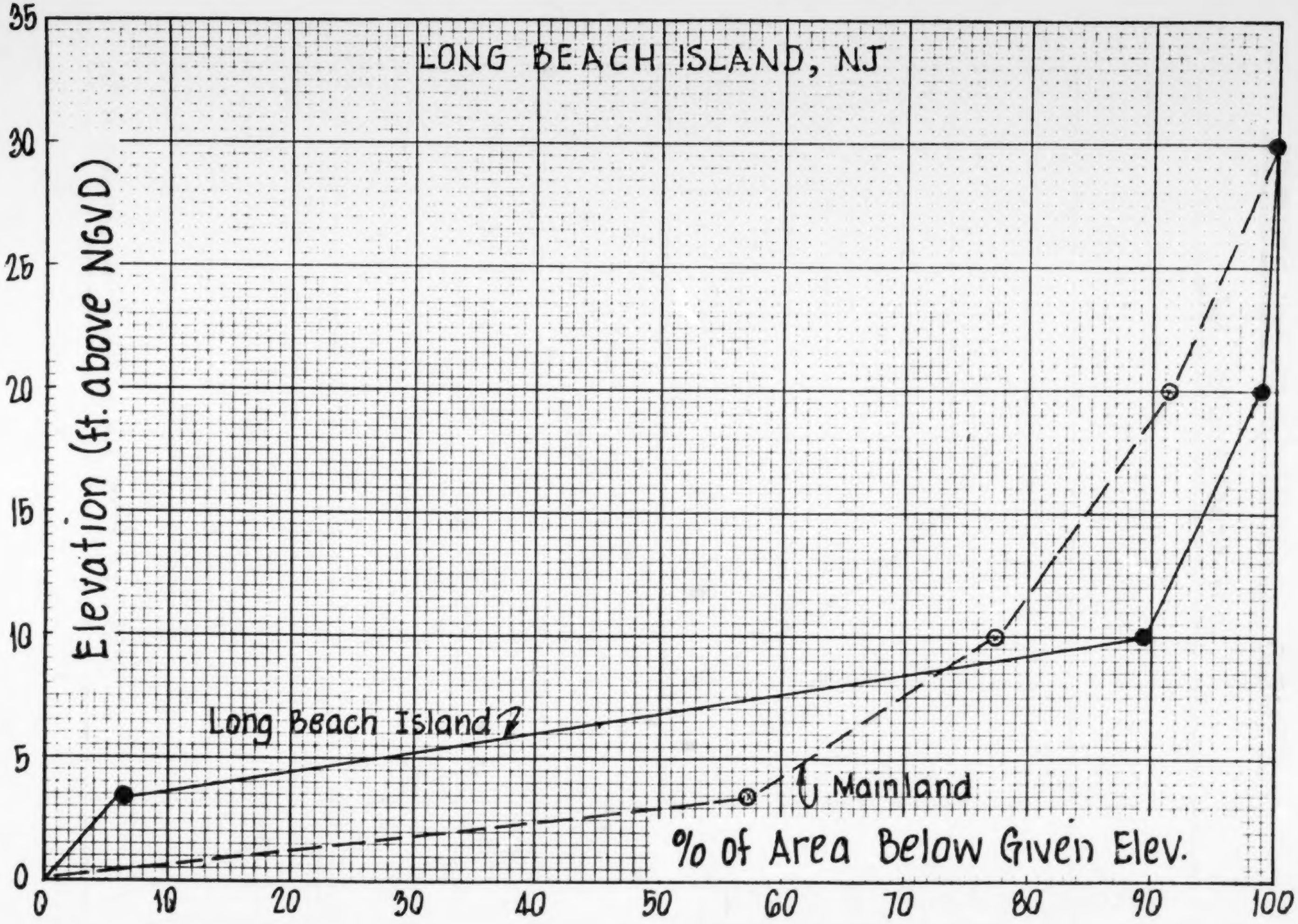


Figure 7 Distribution of Ground Elevation - Long Beach Island and Mainland and Adjacent to Long Beach Island.

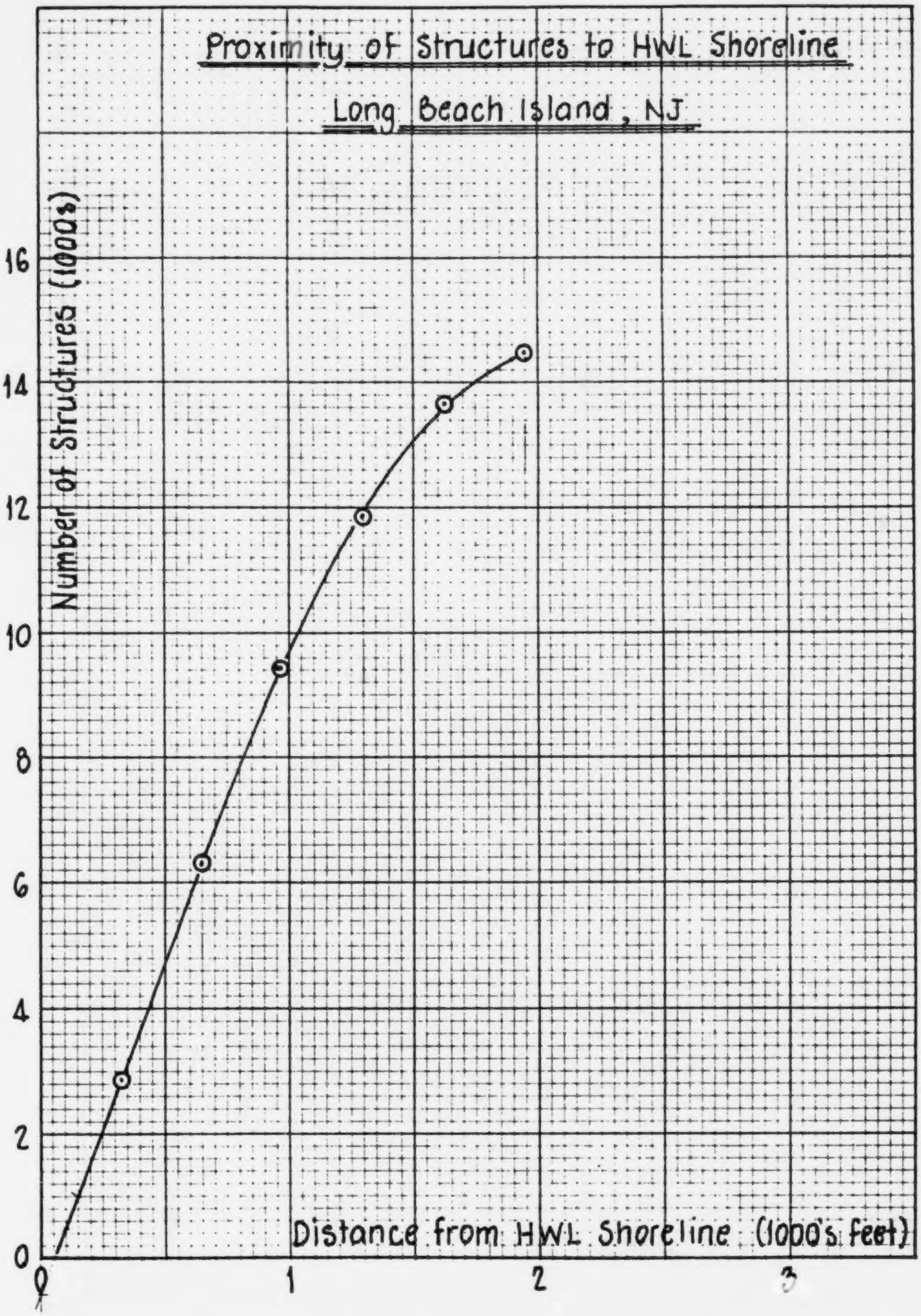


Figure 8 Proximity of Buildings to High Water Shoreline - Long Beach Island (Based on Analysis of 1984 Aerial Photographs).

TABLE 14 DISTRIBUTION OF BUILDINGS ON LONG BEACH ISLAND

Distance from Ocean Shoreline (ft)	Number of Buildings	Cumulative Number	%
0 to 325	2834	2834	19.65
325 to 650	3464	6298	43.67
650 to 980	3110	9408	65.24
980 to 1300	2468	11876	82.35
1300 to 1630	1756	13632	94.52
1630 to 1960	789	14421	100.00

$$N = 10.4\,X - 600 \qquad (3)$$

in which N = the number of buildings affected and X = the distance measured landward from the present high-water shoreline in feet. Equation 3 is valid for values of X between 60 feet and 1000 feet.

Development density varies along the island as shown in Figure 9. In general, building density is lower in the more northerly communities where lot coverage is lower. The area per building, averaged over the entire island, is 12,600 square feet per building or a density of 2,200 buildings per square mile. In the northerly communities of Barnegat Light and Loveladies, about 50% of the homes are of recent construction and are elevated on pilings one floor above ground level.

SEA LEVEL RISE SCENARIO

By 2100, for purposes of this study, mean sea level at Long Beach Island was assumed to be 2 meters above 1986 levels plus that portion of the historically observed sea level rise that exceeds 0.0012 meters per year, i.e., the increase in mean sea level that would occur if the observed historical rate were to prevail (Titus, this volume). At Long Beach Island, the historical rate of sea level rise has been about 0.004 meters per year. Thus, mean sea level is given by the equation,

$$Z = 0.004(YR-1986) + 0.0001424(YR-1986)^2 \qquad (4)$$

where Z is the elevation of mean sea level above the 1986 level (meters) and YR is the year. Thus by 2100, mean sea level at Long Beach Island will be 2.31 meters above the 1986 level. The first term of Equation 4 gives the historical rate, while the second term gives the rate due to the accelerated "greenhouse effect." Equation 4 is plotted in Figure 10 along with sea level curves for other historical rates, i.e., for various values of the coefficient of the first term in equation 4.

A rough estimate of the average rate of shoreline recession for Long Beach Island can be derived from the rate of sea level rise by using the Bruun rule (Bruun, 1962). For the Atlantic coast of the U.S., the profile closure depth is approximately 30 feet. At Long Beach Island, the 30-foot contour is approximately 4,000 feet from shore on average and the dune crests can be assumed to be about 10 feet high. Thus, the profile extending from dune crest to closure depth is about 40 feet high, and a one foot change in mean sea level will result in 4000/40 = 100 feet of shoreline recession. Combining this rate of erosion with the mean sea level curves results in the shoreline recession curve in Figure 11. This curve, given by,

$$X = 328.1\{0.004(YR-1986) + 0.0001434(YR-1986)^2\} \qquad (5)$$

in which X is the shoreline recession in feet. It is simply 100 times the sea level rise curve given by Equation 4.

Coupled with the building density data of Figure 8, the number of houses affected by the rise in sea level can be determined from the shoreline recession curve. Figure 12 shows the number of buildings on Long Beach Island affected by sea level rise as a function of time. The cumulative number of buildings is given by,

$$N = 13.65(YR-1986) + 0.4893(YR-1986)^2 - 600 \qquad (6)$$

for the years after 2010.

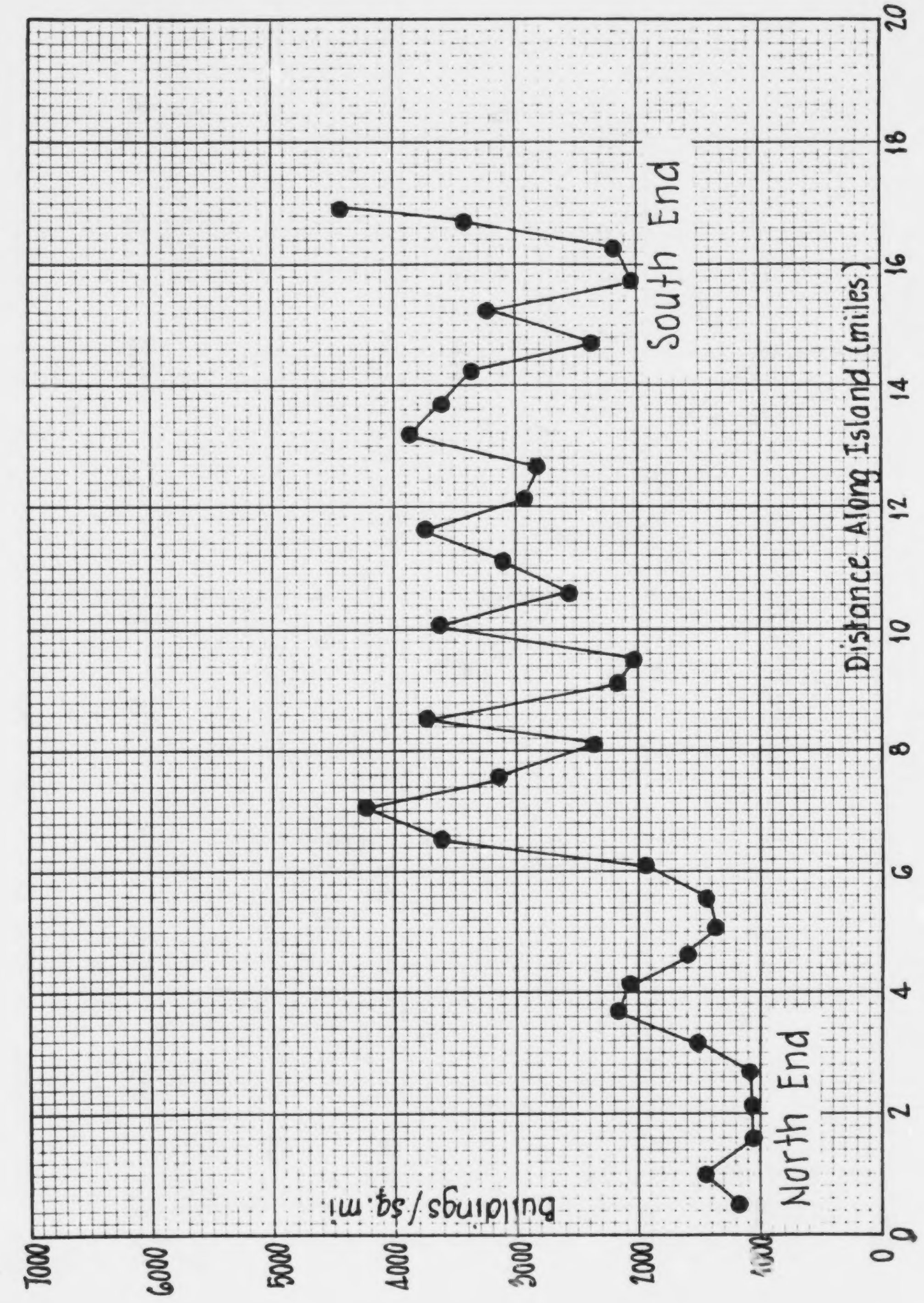


Figure 9 Distribution of Building Density along Long Beach Island (Based on Analysis of 1984 Aerial Photographs).

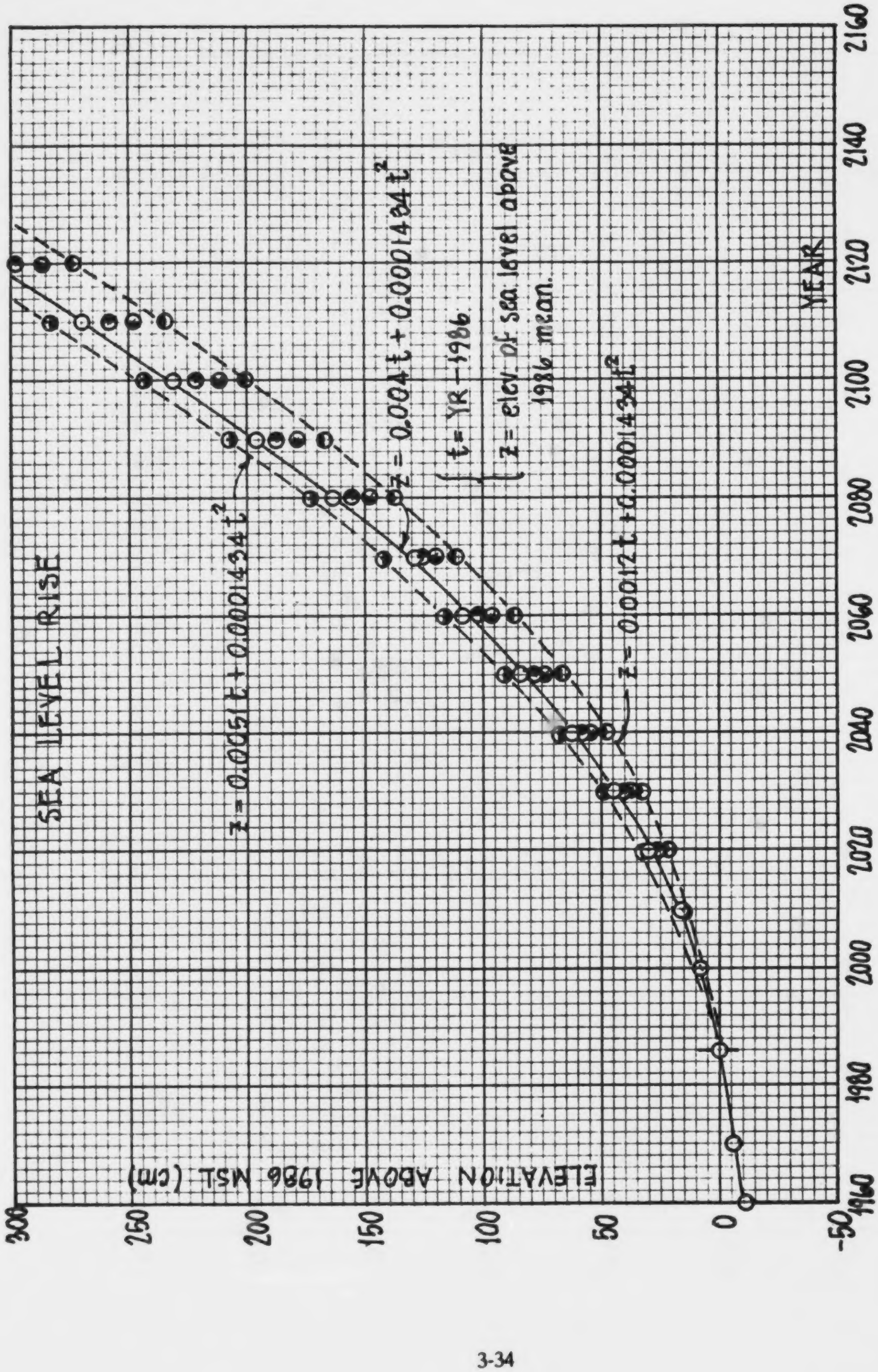


Figure 10 Sea Level as a Function of Time - Long Beach Island.

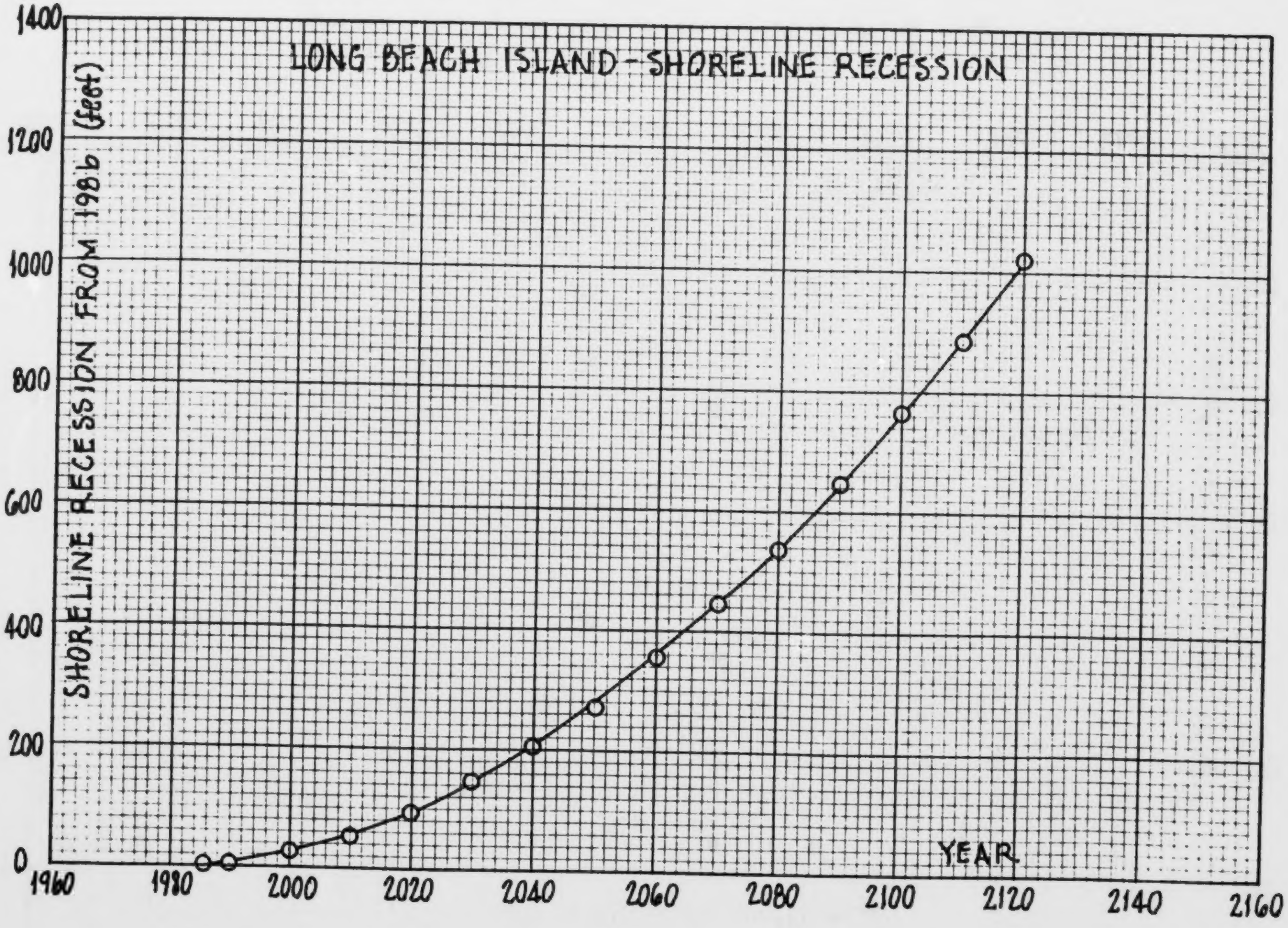


Figure 11 Shoreline Recession as a Function of Time - Long Beach Island.

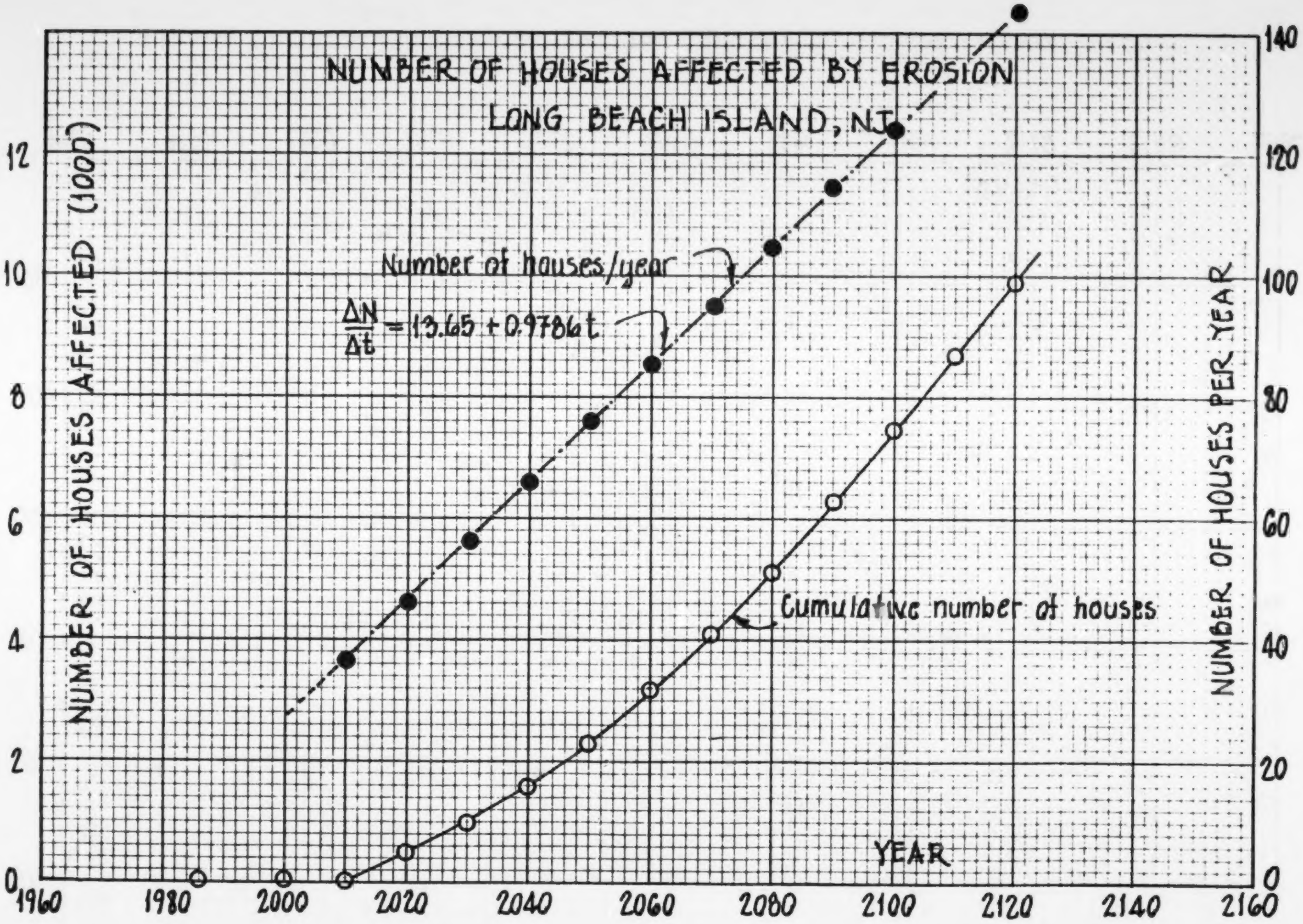


Figure 12 Number of Houses per Year and Cumulative Number of Houses Affected by Sea Level Rise as a Function of Time - Long Beach Island.

Because of the setback of existing buildings behind the dunes, the analysis shows that the buildings closest to the beach are not affected until 2010. Actually, they will feel the effect of sea level rise sometime earlier because of their vulnerability to storm damage as the dune buffer between them and the sea disappears; however, based on the given sea level rise scenario, the buildings will remain landward of the shoreline until 2010. The lower curve of Figure 12, which shows the cumulative number of buildings affected by erosion, should probably be shifted leftward to account for owners abandoning or moving buildings that experience storm damage more and more frequently as the shoreline recedes. The annual rate at which buildings are affected by shoreline recession can be found from the slope of the cumulative number of buildings affected. The rate is given by,

$$R = 13.65 + 0.9786(YR-1986) \qquad (7)$$

in which R = the number of buildings affected per year. Since the cumulative number of buildings varies parabolically, the annual rate at which buildings are affected varies linearly with time. Approximately 37 buildings per year will be affected in 2010. By 2100, however, 125 buildings per year will come within reach of the encroaching shoreline.

RESPONSE TO SEA LEVEL RISE

Reproduce Landward Migration of Barrier Island

One possible response to a rising sea level at Long Beach Island would be to physically introduce a landward migration of the barrier island. As sea level rises and erodes the island's ocean beaches, additional land would be created on the bay side of the island by bulkheading and filling. As buildings are affected by the encroaching ocean shoreline, they would be moved to new land created on the bayward side of Long Beach Island. Initially, fill to create the new land would be obtained from the bay adjacent to the island, possibly by deepening, expanding, or moving the Atlantic Intracoastal Waterway. In later stages, however, the cumulative quantity of fill needed would, like beach nourishment, require the exploitation of offshore sand resources. (See Leatherman, this volume.)

There are three major elements contributing to the cost of this scenario. They are: a) the cost of creating new land and subsequently raising the elevation of the island as high tide levels increase; b) the cost of moving buildings; and c) the cost of replacing infrastructure as it becomes inundated or damaged by the encroaching sea. Some of these costs will be incurred even if sea level does not rise. For example, infrastructure such as roads, highways, buried utilities, etc., must be replaced as their useful lifetime runs out. Also, some buildings would be razed and replaced even without sea level rise. In some cases, a rise in sea level may only reduce the economic lifetime of a structure and hasten its replacement. The true costs attributable to sea level rise are the additional costs that would not have been otherwise incurred, i.e., the cost of replacing a road that would not otherwise require replacement or of replacing the road in 5 years rather than in 10 years.

On Long Beach Island, the number of buildings affected by sea level rise in each year following the year 2010 can be computed from Equation 7. The cumulative number of buildings is given by Equation 6. The average cost of moving a building of the size of those located on Long Beach Island is about $10,000 including the reconstruction of a new foundation. This is the cost to move the building a distance of less than 1/2 mile. Thus in 2010, 37 buildings would be either abandoned to the sea or moved at a cost of $10,000 each (1987 dollars).

Determining the cost of creating additional land to which buildings can be moved requires that the volume of fill needed and its unit cost be determined. The scenario investigated here assumes that fill will be required to raise the land elevation. The land will initially be raised at the same rate as sea level rises. As sea level rises further, starting in 2005, new land will be created at an elevation +1.4 feet above spring high tides. As a first approximation, tidal ranges in the bay behind Long Beach Island were assumed to be unaffected by any increase in mean sea level. Additional land area will also be created at an elevation to keep it at least 1.4 feet above the then-prevailing spring high tides. See Figure 13. The depth of the bay close to shore immediately behind Long Beach Island averages about 4.1 feet below NGVD datum. Actually it ranges from about 1 foot deep over relatively large areas to more than 10 feet deep in some small, restricted areas -- mostly due to nearshore navigation channels and deepened small craft mooring areas. The mean tidal range at several locations behind Long Beach Island is given in Table 15. The average mean tidal range assumed for the present study was 2.2 feet. The mean spring tidal range was taken to be 3.2 feet. From Figure 7, each foot of sea level rise above +3.5 feet would inundate about 13% of the island's area. Thus the portion of the island that would have to be raised is 13% of the island's original 1986 area. New land created after 2005 would be at an elevation exceeding +3.5 feet NGVD to keep it at least 1.4 feet above spring high tides at the then-prevailing mean sea level.

The scenario adopted for the rate of land creation was: a) starting at present, land would be raised at a rate to keep its elevation 1.4 feet above spring high tides; and b) starting in 2005, land would be replaced on the bay side of the island each year at a rate equal to the number of buildings moved each year times an average building lot area of 12,600 square feet, i.e., 12,600 times the value of R given by Equation 7. (The year 2005 rather than 2010 was used as the start of filling in order to account for the possibility that some owners would take preventative action before their buildings were damaged.) Figure 14 shows the volume of fill required each year following 2005 along with the cumulative volume required. The annual amount of fill increases almost linearly with time so that by 2100, about 680,000 cubic yards of fill will be needed each year. A total of 41 million cubic yards of fill will be required by the year 2100!

For this scenario, 12,600 square foot building lots are re-established on the bay side of the island, and the annual volume of fill required between the present and the year 2005 is given by,

$$dV/dt = 12{,}300 + 877(YR-1986) \tag{8}$$

where dV/dt is the rate at which sand must be used to create land in cubic yards per year. The cumulative volume used up to a given year is given by,

$$V = 12{,}300(YR-1986) + 438(YR-1986)^2 \tag{9}$$

for the years between the present and 2005, with V in cubic yards. For the years following 2005, the annual volume and cumulative volume are given by,

$$dV/dt = 73{,}534 + 5{,}273(YR-1986) + 0.427(YR-1986)^2 \tag{10}$$

and,

$$V = -1{,}957{,}900 + 73{,}534(YR-1986) + 2{,}636(YR-1986)^2 + 0.142(YR-1986) \tag{11}$$

respectively.

These equations are plotted in Figure 14.

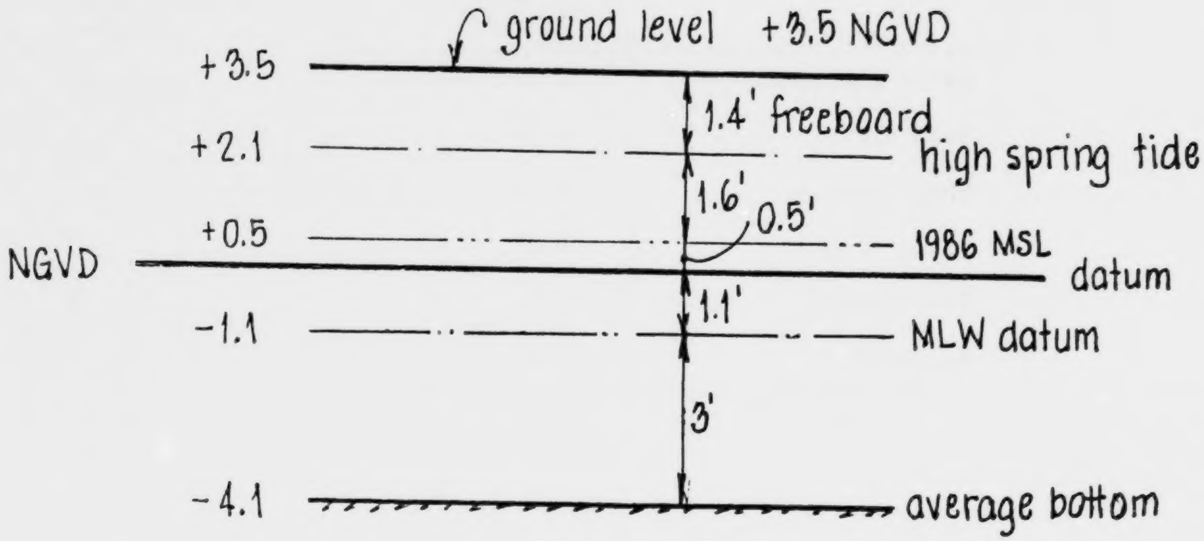

ground level +3.5 NGVD
+3.5
1.4' freeboard
+2.1
high spring tide
1.6'
0.5'
+0.5
1986 MSL
NGVD
datum
1.1'
-1.1
MLW datum
3'
-4.1
average bottom

Figure 13 Datums and Tide Levels in Bay Behind Long Beach Island, NJ

TABLE 15 MEAN TIDAL RANGE IN BAYS BEHIND LONG BEACH ISLAND

Location	Mean Range (feet)
Barnegat Light	2.3
Surf City	1.0
Ship Bottom	1.5
Spray Beach	2.2
Beach Haven	2.2
Holgate	2.4

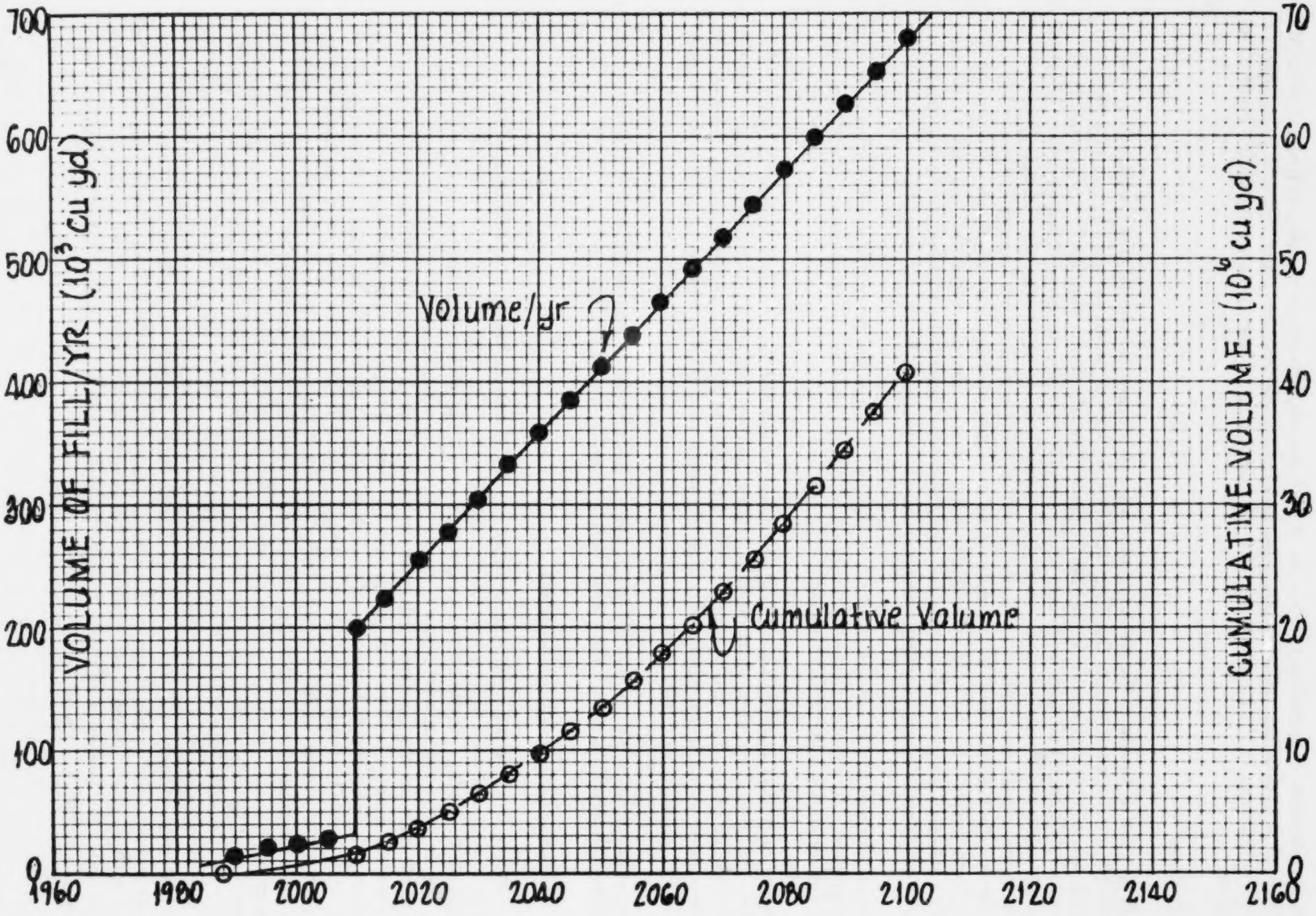


Figure 14 Volume of Fill and Cumulative Volume of Fill Required to Raise Long Beach Island, NJ as a Function of Time.

Three major elements contributing to the costs of implementing this alternative are: a) the cost of fill; b) the cost of replacing infrastructure including roadways and buried utilities (see Table 16); and c) the cost of raising and moving buildings to the landward side of the barrier island. These costs are shown in Figure 15 as a function of time.

Raise Island in Place

A second alternative, similar to the preceding one, is to simply raise the elevation of the island but without moving it landward into shallower water. Buildings would be elevated as necessary and fill placed on the island. Buildings already raised on pilings would simply have fill placed beneath them. Thus the present trend in coastal areas of constructing elevated buildings on pilings would simplify implementation of this alternative. Much of the buried infrastructure might continue to be used. For example, water, and storm and sanitary sewers would still be serviceable for several years. They would simply end up being buried deeper beneath the ground surface. Eventually, however, they would have to be replaced as increased seepage into storm and sanitary sewers becomes a problem because of the relatively higher water table. The sea water environment would also accelerate deterioration of the pipes. Roadways and sidewalks would have to be replaced at the time the island is raised. This would be the major infrastructure replacement expense under this alternative.

The amount of fill required for this scenario is slightly less than the preceding scenario; however, the difference is negligible. The amount of bulkheading is also about the same as for the preceding alternative since the island's perimeter remains the same. See Figure 15a.

The number of houses involved under this alternative would also be somewhat less than the number involved in the preceding alternative, particularly if houses, as they are replaced, are replaced with houses constructed on elevated piling. The cost of simply raising a building in place is also assumed to be less than the cost of both raising and moving it to another site. For this study, however, the number of houses to be raised was assumed to be that given by equation 6.

The three primary elements contributing to the cost of this alternative are: a) the cost of fill; b) the cost of replacing some infrastructure; and c) the cost of raising houses. See Figure 15a.

Dike Around Island and Provide Interior Drainage

A third response to rising sea level along a highly developed barrier island like Long Beach Island, New Jersey, would be to construct dikes and an interior drainage system. The drainage system would have to handle both the seepage under the dike resulting from an elevated sea level as well as the interior runoff resulting from precipitation. The drainage system would have to handle the storm water that might otherwise drain by gravity into the sea. In general, the requirements to handle the runoff from precipitation will initially determine the size of the storm water storage facilities and pumps needed. Since it would be uneconomical to provide pumps having the capacity to drain runoff from rare storms with long return periods, storage facilities capable of holding runoff until it can be pumped into the sea would have to be provided. For the Long Beach Island scenario, relatively small storage facilities located under the street ends along the back side of the island were assumed to provide the most economical storage alternative. Since space is generally not available to construct large storm water storage facilities on Long Beach Island, a number of small tanks capable of holding the runoff from a cross-section of the island about two blocks wide was assumed. Preliminary dimensions for the tanks were what might be reasonably constructed beneath the street ends -- tanks approximately 50 feet wide, 100 to 200 feet long, and 10 to 20 feet deep. The storage capacity of such tanks vary from a minimum of about 50,000 cubic feet to a maximum of about 200,000 cubic feet. Storm water pumping would be episodic with most of it occurring during and after major rain storms. The average annual precipitation at Long Beach Island is about 45 inches per year. This precipitation is not uniformly distributed over time; rather, it occurs during irregularly spaced storm periods. Because of Long Beach Island's relatively small area, the precipitation can be assumed to be uniformly distributed over the island.

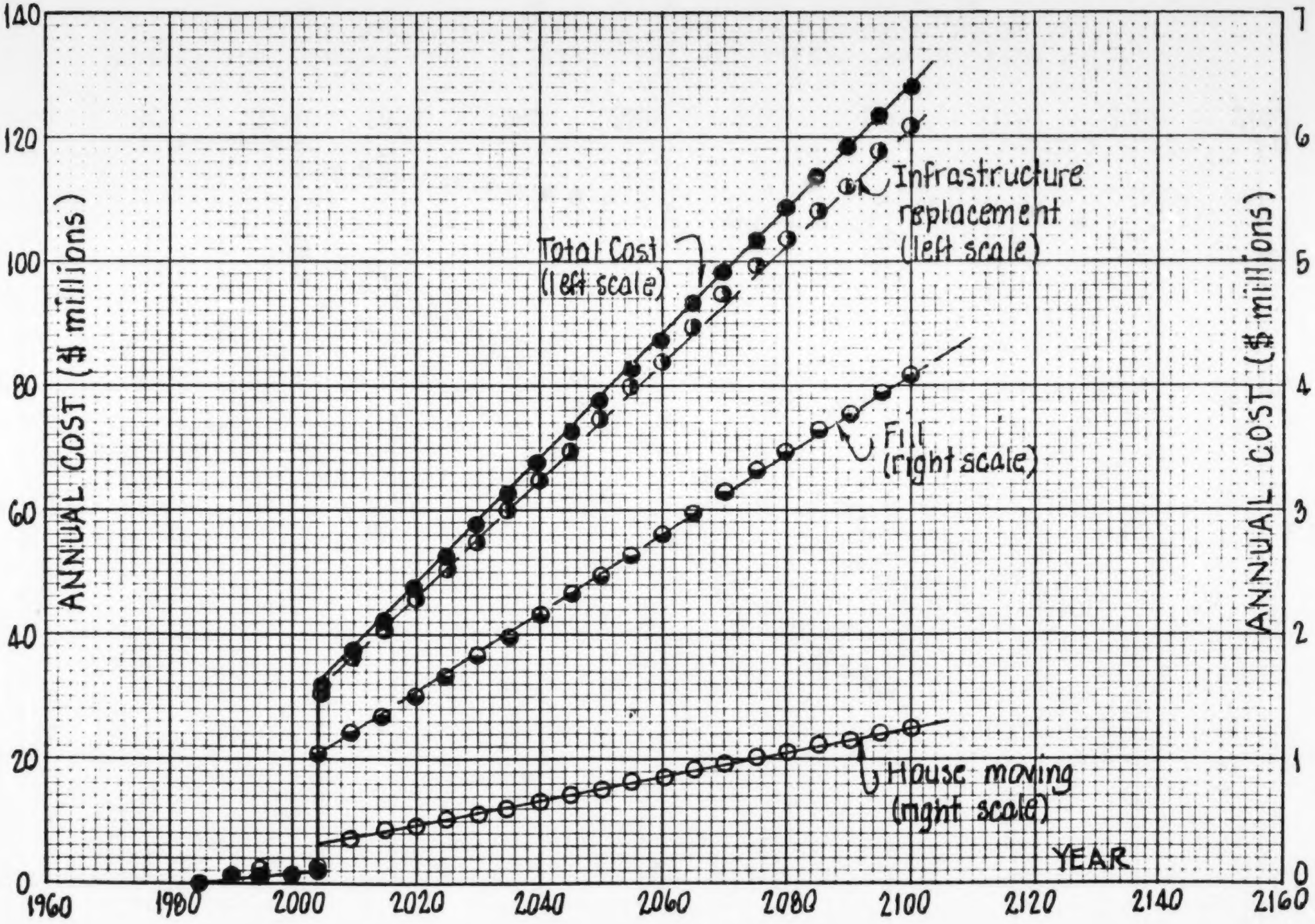


Figure 15 Annual Cost of Fill, Infrastructure Replacement, and House Moving for Long Beach Island, NJ as a Function of Time - Raise and Move Island Alternative.

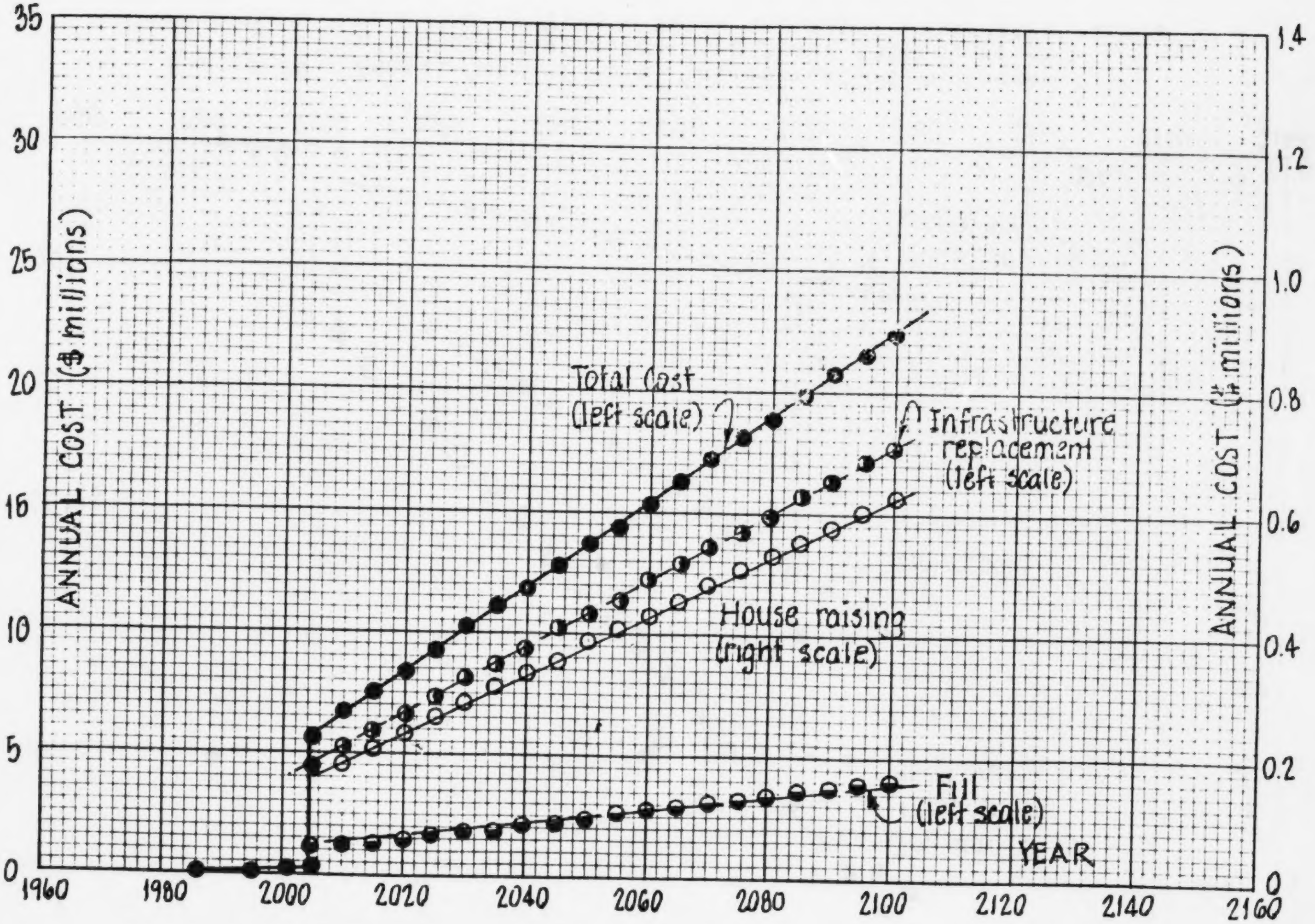


Figure 15a Annual Cost of Fill, Infrastructure Replacement, and House Raising for Long Beach Island, NJ as a Function of Time - Raise Island Alternative.

TABLE 16 HIGHWAYS AND STREETS - LONG BEACH ISLAND, NEW JERSEY

SHORE-PARALLEL ROADS

Primary N-S Road	30.14 mi.
Second Major N-S Road	6.85
Third Major N-S Road	5.21
Total Other N-S Roads	10.83
Total Shore-Parallel	53.03 mi.

SHORE-NORMAL ROADS

Total E-W Roads	70.79 mi.
Total Shore-Normal	70.79 mi.
TOTAL	123.82 mi.

A hydrologic analysis of Long Beach Island was performed to determine the amount of storm runoff that might be expected. This was used to size the storage and pumping facilities needed to handle the runoff. Rainstorms with return periods ranging from 10 to 50 years were investigated and routed through the proposed street-end storage tanks to determine how much interior flooding might result during periods of high runoff when the tank storage capacity is exceeded. Runoff values were calculated using Soil Conservation Service (SCS) methods outlined in "Urban Hydrology for Small Watersheds," Technical Release 55 (SCS TR-55). This method relates the runoff per inch of rainfall to the watershed area, slope, land use, and the condition of the land cover. Rainfall values were obtained from the National Weather Service's Rainfall Frequency Atlas of the United States, Technical Paper No. 40. Storms having return periods ranging from 10 to 50 years with durations ranging from 30 minutes to 24 hours were analyzed. Peak discharges were developed for drainage areas of about 24 acres, the contributing area assumed for each of the individual storage tanks. Peak discharges are given in Table 17 for rainfalls of 24 hours' duration. For a storage tank capacity of 150,000 cubic feet, a pumping capacity of 30 cubic feet per second is required to minimize flooding the interior of the island during major rainstorms. If each individual drainage system drains about 24 acres, about 200 such systems are needed to serve Long Beach Island.

In addition to interior runoff, seawater seepage beneath the dikes will occur, at first only during high tides, but later, as sea level rises and the difference in elevation between mean sea level and the interior land increases, seepage will occur during much of the tidal cycle. As time passes and sea level rises, the amount of seepage will increase. Eventually, it might be necessary to pump almost continuously, albeit at a relatively low rate when compared to stormwater drainage pumping requirements. To control seepage, an interior drainage system of buried drain pipes was investigated. These drains would intercept seepage and convey it to the storage tanks beneath the street ends. During periods of little or no storm runoff, the drainage system would continue to intercept and hold the seepage until the water reached a given level in the tank, at which time a pump would turn on and drain the tank.

Dikes to hold back the sea have long been constructed in Holland where much of the land is beneath the present sea level. Because of its high population density, land reclamation has been economically justified in Holland. It has been a matter of survival. The question remains whether it is economical to protect areas such as Long Beach Island, New Jersey, from a rising sea level. At first, it would be economical since it would only require replacing existing bulkheads with higher, more substantial structures. Bulkheads similar to those now in existence along much of Long Beach Island's bay shoreline would be adequate to protect the land during periods of high spring tides. As existing bulkheads deteriorate, higher bulkheads that also penetrate deeper into the soil would take their place. The cost attributable to sea level rise is only the added cost of building higher, more substantial bulkheads. However, if the rate of sea level rise is so rapid that the bulkheads must be raised or replaced before they reach the end of their useful life, the cost of sea level rise is the value of protection for the remaining lifetime of the bulkhead, which is now no longer adequate to provide protection, plus the added cost of building a new, more substantial bulkhead to replace it. For the present drainage scenario, a substantial concrete sheet pile bulkhead backed by an earth embankment was designed. See Figure 16. The estimated cost per foot of the bulkhead is $500. A sheet pile bulkhead was selected because it can be designed to provide sufficient soil penetration to limit the rate of seepage beneath it. The earth embankment provides lateral stability, and the rubble toe protection prevents scour.

The amount of seepage beneath the sheet pile bulkhead was investigated using a computer program that determines flow patterns beneath a bulkhead and calculates flow rates per unit length of bulkhead into a system of drains on the interior side of the bulkhead. The number and pattern of drains can be selected. Several patterns were investigated. In addition, several depths of penetration for the sheet pile bulkhead were investigated with the computer model. The computed seepage patterns are shown in Figures 17 through 23. Figures 17 and 18 show seepage patterns under a vertical bulkhead for two different depths of soil penetration. Penetration depth is 6 feet in Figure 17 and 10 feet in Figure 18. For a soil permeability of 0.0005 feet per second (typical for sands), the amount of seepage under the wall penetrating 6 feet (Figure 17) is 0.002 cubic feet per second per foot (cfs/ft) of bulkhead. For 10 feet of penetration, the seepage rate is 0.0017 cfs/ft. Figures 19 and 20 show the effect of providing a single drain 4 feet below the ground surface and 4 feet behind the bulkhead, for 6 feet and 10 feet of pile penetration, respectively. The amount of seepage into the drain is

TABLE 17 SUMMARY OF RAINFALL FREQUENCY ANALYSIS - 24 HOUR RAINFALL

Recurrence Interval (yrs)	Rainfall Depth (in)	Runoff Depth (in)	Peak * Discharge (cfs)
1	2.8	1.1	7
5	4.5	2.2	33
10	5.5	2.9	44
25	6.0	3.5	53
50	6.6	4.0	60

* Maximum peak flow of hydrograph derived from SCS TR-55 method.

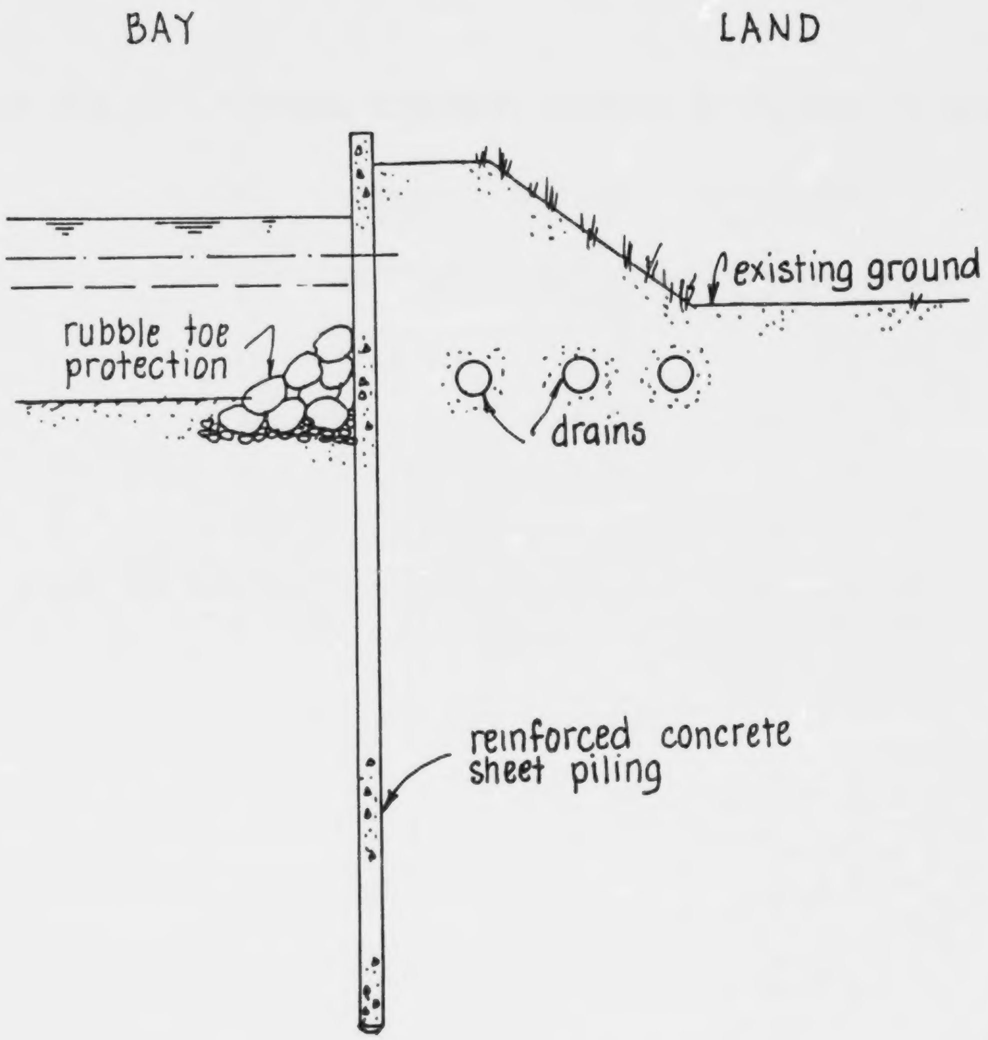
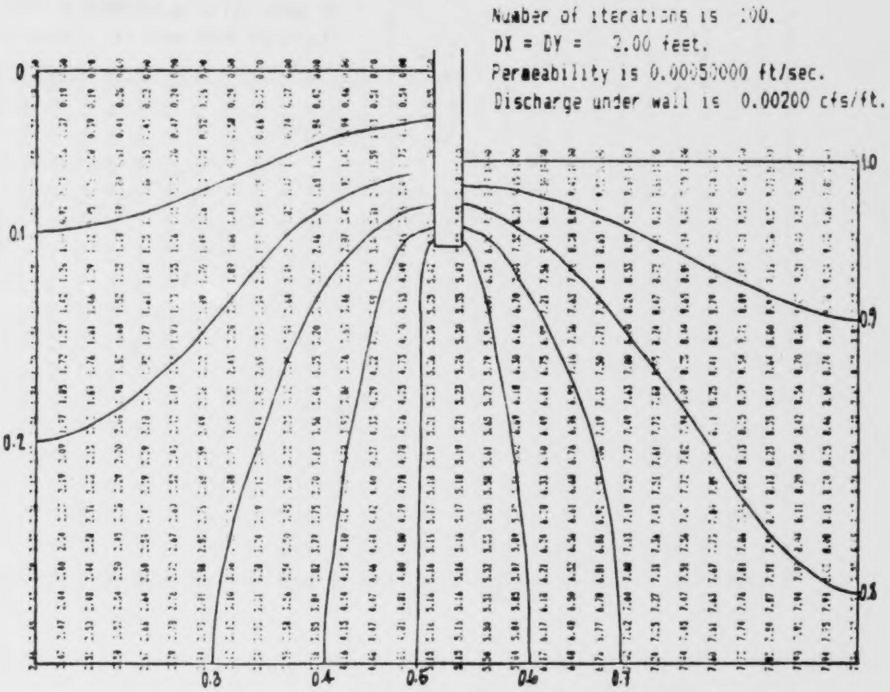

BAY
LAND
existing ground
rubble toe protection
drains
reinforced concrete sheet piling

Figure 16 Typical Cross-Section for Concrete Sheet Pile Bulkhead/Dike.



```
Number of iterations is  100.
DX = DY =   2.00 feet.
Permeability is 0.00050000 ft/sec.
Discharge under wall is  0.00200 cfs/ft.
```

Figure 17 Seepage Under Sheet Pile Cutoff Wall - 6 foot Penetration, No Drains.

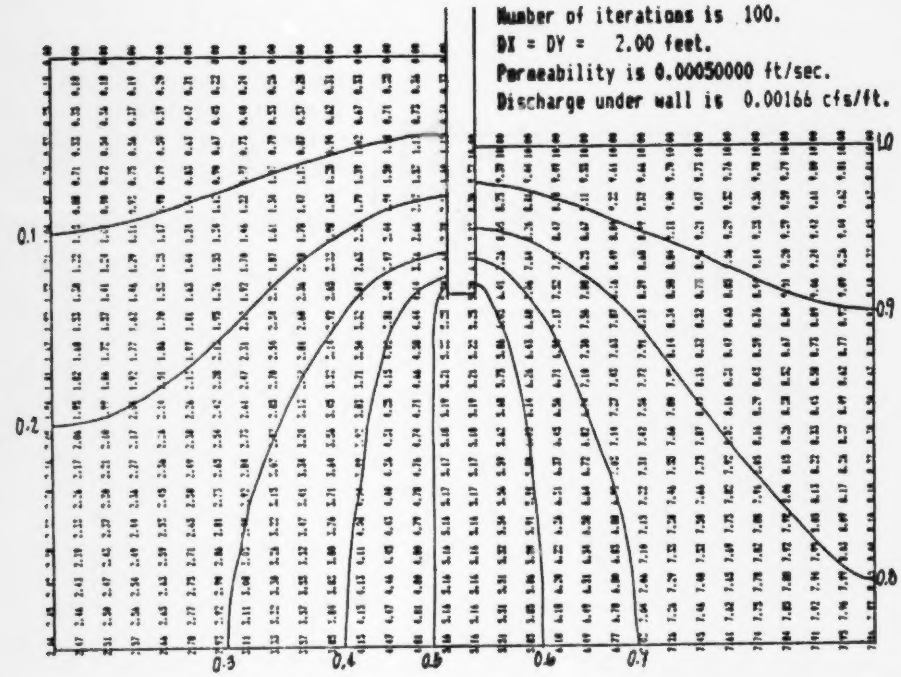
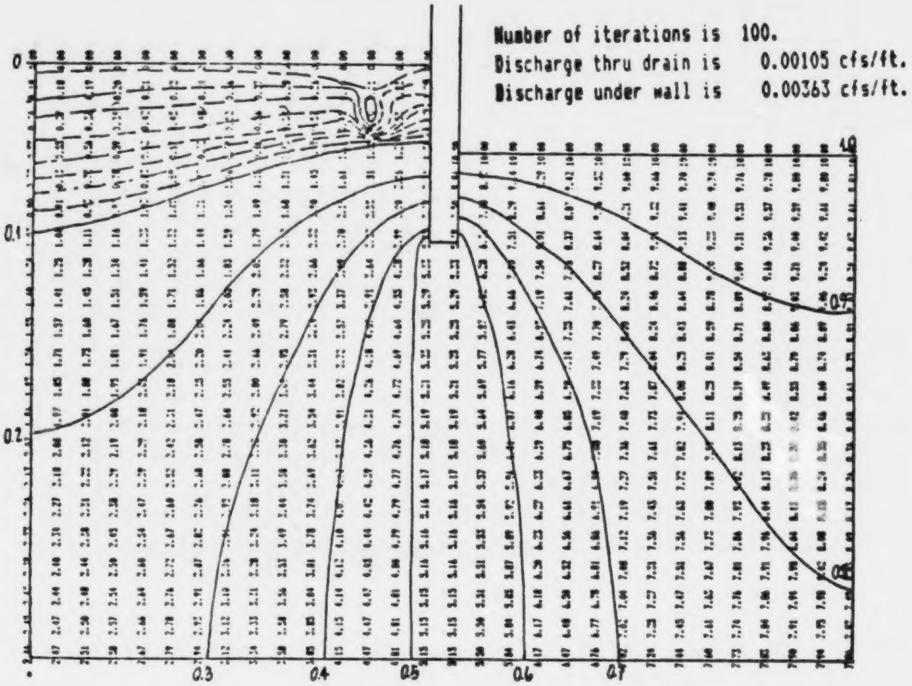
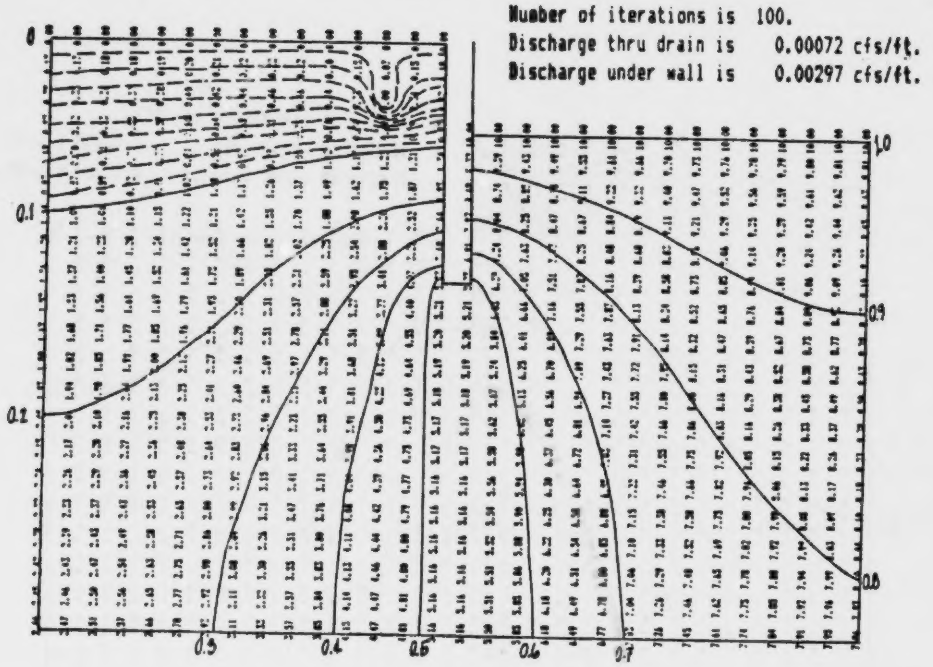


Figure 18 Seepage Under Sheet Pile Cutoff Wall - 10 foot Penetration, No Drains.



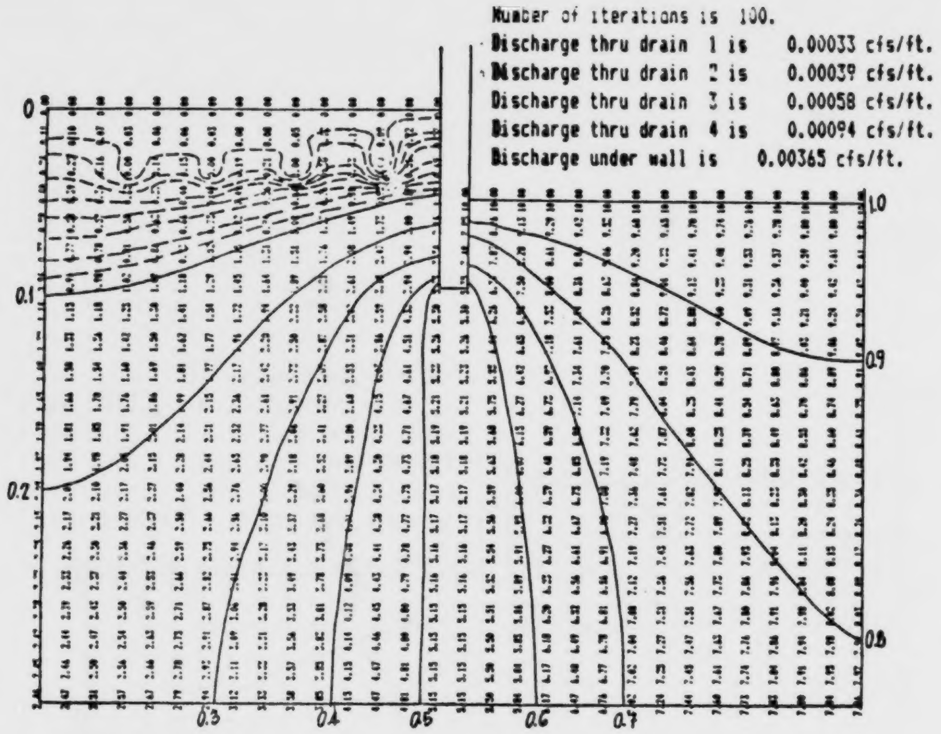
```
Number of iterations is  100.
Discharge thru drain is     0.00105 cfs/ft.
Discharge under wall is     0.00363 cfs/ft.
```

Figure 19 Seepage Under Sheet Pile Cutoff Wall - 6 foot Penetration, One Drain.



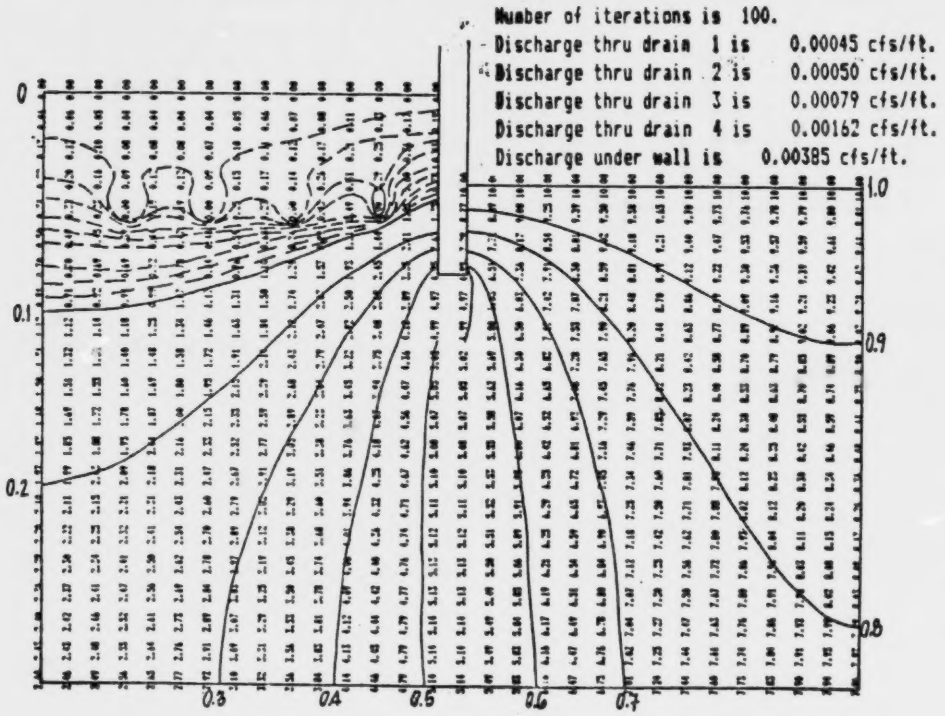
```
Number of iterations is  100.
Discharge thru drain is     0.00072 cfs/ft.
Discharge under wall is     0.00297 cfs/ft.
```

Figure 20 Seepage Under Sheet Pile Cutoff Wall - 10 foot Penetration, One Drain.



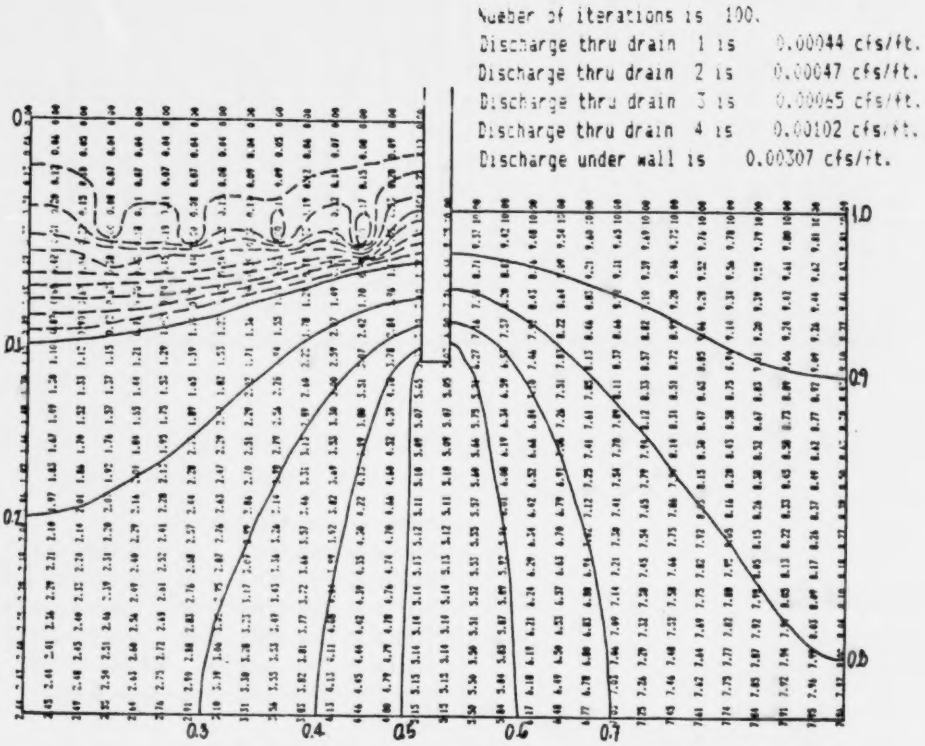
```
Number of iterations is  100.
Discharge thru drain  1 is     0.00033 cfs/ft.
Discharge thru drain  2 is     0.00039 cfs/ft.
Discharge thru drain  3 is     0.00058 cfs/ft.
Discharge thru drain  4 is     0.00094 cfs/ft.
Discharge under wall is    0.00365 cfs/ft.
```

Figure 21 Seepage Under Sheet Pile Cutoff Wall - 6 foot Penetration, Four Drains 4 feet Below Ground.



```
Number of iterations is  100.
Discharge thru drain  1 is     0.00045 cfs/ft.
Discharge thru drain  2 is     0.00050 cfs/ft.
Discharge thru drain  3 is     0.00079 cfs/ft.
Discharge thru drain  4 is     0.00162 cfs/ft.
Discharge under wall is    0.00385 cfs/ft.
```

Figure 22 Seepage Under Sheet Pile Cutoff Wall - 6 foot Penetration, Four Drains 8 feet Below Ground.



```
Number of iterations is  100.
Discharge thru drain  1 is    0.00044 cfs/ft.
Discharge thru drain  2 is    0.00047 cfs/ft.
Discharge thru drain  3 is    0.00065 cfs/ft.
Discharge thru drain  4 is    0.00102 cfs/ft.
Discharge under wall is    0.00307 cfs/ft.
```

Figure 23 Seepage Under Sheet Pile Cutoff Wall - 10 foot Penetration, Four Drains 8 feet Below Ground.

0.00105 cfs/ft, while the total seepage rate under the wall is 0.00363 cfs/ft. Only about 29% of the seepage is intercepted by the drain. Figure 23 shows the configuration finally adopted as typical for a drainage system for Long Beach Island. Drains are located 8 feet below the ground surface, spaced 6 feet apart, with the closest drain about 4 feet behind the bulkhead. The total discharge under the wall is 0.0031 cfs/ft, while the drains intercept a total of 84% of the flow beneath the bulkhead. (Note that the total seepage intercepted by the drains is not 100% because of simplifying assumptions made in the program.) The results of the seepage analysis are summarized in Table 18.

Elements contributing to the cost of implementing this alternative are: a) the construction of new bulkheads along the portion of the shoreline not now bulkheaded; b) the cost of constructing raised bulkheads; c) the cost of the interior drainage system; d) the cost of the storm water detention tanks; e) the cost of the pumps and pumping stations; and f) the cost of electrical power to operate the pumping system.

SUMMARY OF COSTS OF ALTERNATIVES AT LONG BEACH ISLAND

The cost of each of the three assumed alternative actions at Long Beach Island was evaluated. The unit costs assumed in the analysis along with the lifetime of each element are given in Table 19. Fill was assumed to cost about $6.00 per cubic yard. This is an average cost for hydraulically dredged fill obtained from the bay areas and later from offshore sources as nearshore sources are depleted. The drainage system involves Figure costs for the storage facilities, pumps, street and sidewalk replacement, and the drainage pipes. Major elements of the system such as the storage facility were assumed to have a lifetime of 50 years. Other elements, such as the pumps, were assumed to have shorter lifetimes. The $300,000 cost reflects the shorter lifetime of those elements such as pumps, etc., and assumes their replacement over the 50-year lifetime of the entire system.

The costs of the three alternatives investigated for Long Beach Island are summarized in Table 20.

Raising the island in place is estimated to cost $1.36 billion. Most of this cost is associated with replacing roadways, sidewalks, and other above-ground utilities as the island is raised. The cost of fill is estimated at $247 million, and the cost of raising buildings is estimated at $37 million.

Moving the island landward and raising it in response to sea level rise is estimated to cost $7.67 billion. The major cost, that of replacing the infrastructure, is $7.35 billion. This includes replacing all of the buried utilities, a major factor in establishing the higher cost of this alternative when compared with the preceding alternative. The cost of raising and moving houses under this alternative is $74 million. The cost of raising and moving a house is assumed to be twice the cost of simply raising a house. Also, with the replacement of houses by houses elevated on piling over the years, there will probably be fewer houses that will have to be raised at the time the island is raised.

The third alternative, that of providing a dike around the island and providing an interior drainage system, appears to be the least expensive alternative with a total overall cost of $542 million. Most of this cost, $285 million, is associated with the construction of a dike system, assumed to occur in the year 2028. Construction of the interior drainage system and its operation contributes $137 million to the cost. Power was assumed to be available at $0.12 per kWh and the drainage system was assumed to operate for about 1000 hours per year. Each of the nearly 200 storage/pumping systems was assumed to have an overall efficiency of 50% and to pump at the rate of 30 cubic feet per second against a head of 20 feet for the 1000 hours.

Constructing new bulkheads and raising existing bulkheads contributes about $20 million to the cost of this alternative. These costs are incurred between the present and the year 2028, when the bulkheads would be abandoned in favor of a major dike system. The cost of raising bulkheads is discussed below. In general, the only cost included here is the added cost of replacing existing or new bulkheads with higher bulkheads at the end of their useful lifetime.

TABLE 18 SUMMARY OF SEEPAGE ANALYSIS BENEATH SHEET PILE BULKHEADS

Case	No. of Drains	Depth of Penetration (ft)	Discharge Under Wall (cfs/ft)	Discharge to Drains (cfs/ft)	Percent Interception
I (Fig. 17)	0	6	0.0020	0	0
II (Fig. 18)	0	10	0.0017	0	0
III (Fig. 19)	1	6	0.0036	0.0011	29
IV (Fig. 20)	1	10	0.0030	0.0007	24
V (Fig. 21)	4	6	0.0037	0.0022	62
VI (Fig. 22)	4	6	0.0039	0.0034	87
VII (Fig. 23)	4	10	0.0031	0.0026	84

TABLE 18 ASSUMED UNIT COSTS

ITEM	LIFETIME	UNIT COST
Bulkheads	10 yr	$ 130.00/ft
Fill	-	$ 6.00 cu yd
Dike System	50 yr	$ 500.00/ft
Raising Houses	-	$ 5.000 ea
Raising & Moving Houses	-	$ 10,000 ea
Drainage System (storage tanks, pumps & drainage pipes)	50 yr	$ 300,000 ea
Infrastructure		
Roadway 2-lane		$ 150.00/ft
Roadway 4-lane		$ 290.00/ft
Sanitary sewer		$ 180.00/ft
Storm sewer		$ 110.00/ft
Water		$ 20.00/ft
Gas		$ 20.00/ft
	TOTAL 2-lane	$ 480.00/ft
	4-lane	$ 620.00/ft

TABLE 20 SUMMARY OF COSTS OF THREE LONG BEACH ISLAND ALTERNATIVES

ALTERNATIVE (Cost Item)	AVG ANNUAL COST *	CUMULATIVE COST **
Raise Island in Place		
Fill	$ 2.2 million	$ 247 million
Infrastructure (roads only)	9.4 million	1,072 million
Raise buildings	0.3 million	37 million
TOTALS	$ 11.9 million	$ 1,356 million
Raise & Move Island Landward		
Fill	$ 2.2 million	$ 247 million
Infrastructure (roads & buried utilities)	64.5 million	7,352 million
Raise & move buildings	0.6 million	74 million
TOTALS	$ 67.3 million	$ 7,673 million
Dike Island and Provide Interior Drainage System		
New Bulkheads	0.1 million	12 million
Raise Bulkheads (added cost between the years 1986 and 2028)	0.1 million	8 million
Dike System (constructed in 2028)	2.5 million	285 million
Drainage System	0.5 million	57 million
(system operation)	1.6 million	180 million
TOTALS	4.8 million	542 million

* Cumulative total cost divided by 114 years. Note, however, that all costs may not extend over the entire 114 year period.

** Total costs incurred between the years 1986 and 2100.

CHAPTER 5

SUMMARY OF ACTIONS AND THE COST OF RESPONDING TO SEA LEVEL RISE AT INDEX SITES

The USGS quads for each of the index sites was studied, and a strategy for responding to a rising sea level was determined for the site. Specifically, the elevation of developed areas was considered, and those areas below +10 feet NGVD were considered for protection. If a reasonable level of development was present, a dike system to surround the development or to tie it in with high ground was proposed as the response. The length of the dike required was determined from the map. The unit cost of constructing a dike was assumed to be about $500 per linear foot of dike. If the diked area was isolated, and connected to surrounding high land by roads at a low elevation, the cost of raising the elevation of the roadway and/or replacing it was included in the cost of responding to sea level rise. In general, a two-lane highway was considered as the connecting link and its cost determined. The unit cost of replacing a two-lane highway was assumed to be $480 per lineal foot. The cost of replacing a four-lane highway was $620 per foot. These figures include the cost of replacing utilities buried beneath the roadway, lighting, and drainage.

If the shoreline is already protected by existing bulkheads, the length of the existing bulkhead was determined and consideration given to raising and/or replacing it as sea level rises. The total cost of replacing the bulkhead was not attributed to sea level rise, but rather an analysis of the cost of replacing the bulkhead with a higher bulkhead was made. That portion of the cost of raising bulkheads attributable to an increase in the mean sea level is made up of two components: the added cost, over and above the bulkhead's replacement cost, of having to build a higher bulkhead at the end of its useful lifetime, and the cost of replacing the bulkhead early because it does not provide sufficient protection against a rising sea level. For the present study, only the former costs are considered, i.e., the bulkhead's design is assumed to adequately consider the projected increase in sea level so that a rise in sea level does not require its early replacement, but rather, deterioration of the materials or some other mode of failure is the cause for its replacement.

The cost of raising bulkheads depends on the initial cost per lineal foot of the bulkhead, its initial height, its useful lifetime (how often it needs to be replaced), and the increase in bulkhead height whenever it needs to be replaced. The required increase in bulkhead height will vary with time, since the rate at which sea level is projected to rise varies with time. Bulkhead costs vary approximately with the 1.5 power of the height. Thus, a cost increase factor was calculated based on the increase in sea level during the bulkhead's lifetime. For example, for a bulkhead with a lifetime of 20 years, the increase in sea level over 20 years was used to compute the increase in bulkhead height necessary. Obviously, the increase in height depends on what point in time the bulkhead is replaced, since the rate at which sea level is rising is projected to increase. The cost increase factor was defined as the increased bulkhead height divided by its original height raised to the 1.5 power. The cost increase factor multiplied by the initial bulkhead cost (1986 dollars) gives the new bulkhead cost (1986 dollars). The length of bulkhead to be replaced each year was taken to be the total bulkhead length divided by the bulkhead's lifetime.

Assuming an initial bulkhead height of 5 feet, replacement every 10 years, and an initial cost of $130.00 per foot, the added cost per foot of bulkhead per year averaged over the 114-year period between 1986 and 2100 is about $1.60. This will be lower during the early years of the 114-year period but will be higher toward the end of the next century. The total cost for the time period extending to the year 2100 will be the total bulkhead length required times the increased cost per foot per year times 114 years. For 1 mile of bulkhead, this amounts to expending more than $1.2 million just to replace existing bulkheads at the end of their lifetime with the required higher bulkheads.

For areas that are presently unbulkheaded, consideration was given to the need for new, additional bulkheading to protect vulnerable, low-lying areas. New bulkheading was assumed to cost $130 per lineal foot. This represents the present (1988) cost of aluminum sheet piling, about 13 feet long with a concrete cap and anchors.

For buildings located in sparsely developed areas where construction of a dike system would not be economical, consideration was given to moving individual structures to higher ground. Again, not all structures would be moved under such circumstances. The decision to move a structure would depend on its value, its condition, its movability, and the availability of high land within a reasonable distance to which the structure could be moved. It was assumed that about one-half of the buildings identified on the USGS quads would be moved. That is, half of the isolated buildings were considered to be candidates for moving; however, the number of buildings shown on the undeveloped (unshaded) areas of the USGS quads may not be representative of the actual number of buildings present because of development that may have occurred since the time the quads were last corrected. Therefore, the number of buildings on the quads was used to estimate the cost of moving structures. The unit cost of moving a structure was assumed to be about $10,000 based on recent costs to move a 1000 square foot house a distance of about 1/2 mile. This figure includes the cost of preparing a new, simple foundation system (simple footings or concrete slab). Obviously, larger structures and moves of more than 1/2 mile would increase this cost.

The summary of actions that might be taken at each of the index sites is given in Table 21.

COST OF RESPONDING TO SEA LEVEL RISE AT INDEX SITES

The costs of responding to sea level rise at the six index sites are given in Table 22. The costs in the table are the total costs that would be incurred during the 114-year period between 1986 and 2100, which are attributable just to the increase in sea level. Structure replacement costs that would be incurred if sea level remained at its present level have been subtracted. Where bulkheads are already present or are needed to respond to higher sea levels, the cost of replacing them with higher bulkheads at the end of their useful lifetime overshadows most of the other costs considered. The cost for the New York index site is $275 million, with $205 million of that attributable to raising the existing and proposed bulkheads. Where bulkheading is not considered to be practical because of low levels of economic development, the costs are significantly less. For example, at Dividing Creek, New Jersey, only 6.1 miles of new bulkheading appear justified and the cost is only $5.8 million, most of it associated with raising 7.2 miles of highway. The Long Beach Island area cost figures on Table 22 are given for both the mainland behind the barrier island and for the island and mainland combined. Note that the cost of raising the roads on Long Beach Island are not included.

USGS TOPOGRAPHIC DATA ANALYSIS - INDEX SITES

In order to extrapolate the results from the six index sites to a sub-set of the sites investigated by Park et al. (this volume), the topographic and economic development conditions at the six index sites were compared with the conditions at Park's sites. These comparisons were subsequently used to determine the cost of responding to sea level rise at Park's sites. Topography digitized from USGS quads (Park et al., this volume) was used to determine the distribution of land elevations and shoreline lengths at the six index sites. For most of the sites, a spatial matrix of ground elevations averaged over a 500- by 500-meter pixel was available. For the New York and Corpus Christi areas, elevations were averaged over a 250- by 250-meter pixel. A histogram of the distribution of elevations was determined by summing the number of pixels having an elevation within a given elevation interval. For the land elevation histograms, 10 intervals of 1 foot each between elevations 0 and 10 feet NGVD were selected for the analysis. In addition, the number of pixels with elevations above the 10-foot elevation and the total number of pixels with elevation above 0 feet NGVD were determined. In addition, a simple algorithm was developed to estimate the shoreline lengths for each of the index sites. The length of the shoreline was determined using an algorithm that sweeps the elevation matrix two columns at a time and two rows at a time and assigns a shoreline length to the resulting four-pixel pattern, depending on the number of pixels with elevations above zero. If all four pixels are above 0 or below 0, no shoreline length is assigned. If one or three pixels are at 0 or below, the shoreline length assigned is 1.414 times the length of the side of a pixel. If two pixels are at 0 elevation or below, the length of shoreline assigned is either 1.0 times the length of a side or 2.828 times the length of side, depending on the pattern of land and water pixels. If the land pixels are

TABLE 21 SUMMARY OF ACTIONS REQUIRED AS SEA LEVEL RISES AT INDEX SITES

Index Site & USGS Quad	New Bulk. (mi)	Raise Exist. Bulkhead (mi)	Buildings to Move (#)	Highway to Raise (mi)
NEW YORK, NY AREA				
Weehawken	29.50	21.32	21	2.89
Arthur Kill	5.93	4.03	27	-
Brooklyn	2.28	14.91	-	-
The Narrows	6.69	3.50	-	-
Jersey City	11.25	58.89	-	-
Elizabeth	9.92	-	-	-
Central Park	17.52	30.19	-	-
SUB TOTAL	83.09	132.84	48	2.89
LONG BEACH ISLAND, NJ AREA				
Ship Bottom *	0.67	-	139	1.49
Tuckerton *	3.73	-	135	-
Long Beach NE *	-	-	-	-
Beach Haven *	-	-	-	-
SUB TOTAL	4.40	0	274	1.49
* Excludes Long Beach Island itself.				
DIVIDING CREEK, NJ AREA				
Port Norris	2.38	-	152	0.37
Fortescue	2.68	-	20	0.45
Cedarville	-	-	190	3.28
Dividing Creek	1.04	-	116	3.06
SUB TOTAL	6.10	-	478	7.16
MIAMI, FL AREA				
North Miami	12.83	22.37	-	2.54
Miami	2.83	79.06	27	-
SUB TOTAL	15.66	101.43	27	2.54
CORPUS CHRISTI, TX AREA				
Oso Creek NE	15.86	9.10	82 **	5.97
Portland	-	-	8	3.73
Crane Island NW	-	2.39	83	2.24
Port Ingleside	-	2.98	111	4.18
SUB TOTAL	15.86	14.47	284	16.12
** Includes trailer park structures				
SAN FRANCISCO, CA AREA				
Redwood Point	0.89	-	83	1.49
Newark	0.60	6.56	28	2.53
Palo Alto	0.89	6.41	8	1.34
Mountain View	1.49	3.43	84	0.75
SUB TOTAL	3.87	16.40	203	6.11
TOTALS	113.32	265.14	1287	36.31

Table 22. COSTS ASSOCIATED WITH SEA LEVEL RISE AT INDEX SITES

New York Area, NY & NJ			
New Bulkheads	83.1 mi		$ 57.0 million
Raise Bulkheads	215.9 mi		205.3 million
Move Buildings	48		0.5 million
Raise Highways	2.9 mi		9.5 million
		Total	$272.3 million
Long Beach Island Area, NJ (Mainland only)			
New Bulkheads	4.4 mi		$ 3.0 million
Raise Bulkheads	4.4 mi		4.2 million
Move Buildings	270		2.7 million
Raise Highways	1.5 mi		3.8 million
		Total	$ 13.7 million
Long Beach Island Area, NJ (Mainland and bulkheading on back side of island)			
New Bulkheads	17.2 mi		$ 11.9 million
Raise Bulkheads	36.7 mi		35.0 million
Move Buildings	270		2.7 million
Raise Highways	1.5 mi		3.8 million
		Total	$ 53.4 million
Dividing Creek Area, NJ			
New Bulkheads	6.1 mi		$ 4.2 million
Raise Bulkheads	6.1 mi		5.8 million
Move Buildings	478		4.8 million
Raise Highways	7.2 mi		18.2 million
		Total	$ 33.0 million
Miami & Miami Beach Area, FL			
New Bulkheads	15.7 mi		$ 10.8 million
Raise Bulkheads	117.1 mi		111.3 million
Move Buildings	27		0.3 million
Raise Highways	2.5 mi		8.3 million
		Total	$130.7 million
Corpus Christi Area, TX			
New Bulkheads	15.9 mi		$ 10.9 million
Raise Bulkheads	30.3 mi		28.8 million
Move Buildings	284		2.8 million
Raise Highways	16.1 mi		40.9 million
		Total	$ 83.4 million
San Francisco Bay Area, CA			
New Bulkheads	3.9 mi		$ 2.7 million
Raise Bulkheads	20.3 mi		19.3 million
Move Buildings	203		2.0 million
Raise Highways	6.1 mi		20.0 million
		Total	$ 44.0 million

diagonally opposed, the shoreline length factor is 2.828, while if the land pixels are adjacent to one another, the shoreline length factor is 1.0. Because of the coarse size of the pixels (500 meters x 500 meters), in most cases, the algorithm underestimates the length of the actual shoreline, since small variations in the actual shoreline are replaced by straight line segments. For engineering purposes, the estimate is probably sufficient since erosion/flood control structures such as bulkheads are constructed in straight-line segments to minimize their length rather than along the lines of a tortuous shoreline. A correlation between shoreline lengths determined from the digitized data and shoreline lengths found from planimetering the USGS quads is shown in Figure 24. The index site corresponding to each point is indicated on the figure. The data are scattered about the 45 degree line of equality.

Table 23 provides topographic information on the six index sites where the overall distribution of ground level elevations is given. These data were determined by planimetering the USGS quads. Table 24 provides topographic, shoreline length, and the slope of the land below given elevations as determined from the quads, while Table 25 provides similar data as determined from the digitized topographic data. Shoreline lengths obtained from the digitized topographic data analysis are given in Table 26 for the six index sites as well as for 78 additional coastal locations around the U.S.

TABLE 23 SUMMARY OF INDEX SITE TOPOGRAPHIC CONDITIONS
(Based on total land area)

Elevation (ft)	Z<5	Z<10	Z<15	Z<20	Z<25	Z<30	Z<35	Z<40	Total
LONG BEACH ISLAND, NJ AREA									
USGS Area below Elevation	22.5	36.5	-	42.6	-	45.9	45.9	45.9	45.9
USGS % below Elevation	49.1	79.4	-	92.8	-	100.0	100.0	100.0	100.0
Digitized USGS % below Elev	51.0	61.6	76.8	77.1	78.4	78.7	78.7	78.7	100.0
DIVIDING CREEK, NJ AREA									
USGS Area below Elevation	48.2	72.6	-	87.3	-	94.1	94.1	94.1	94.1
USGS % below Elevation	55.2	83.2	-	92.8	-	100.0	100.0	100.0	100.0
Digitized USGS % below Elev	35.6	49.3	98.7	99.0	99.4	99.6	99.7	99.8	100.0
MIAMI, FL AREA									
USGS Area below Elevation	22.6	78.5	107.2	109.1	109.1	109.1	109.1	109.1	109.1
USGS % below Elevation	20.7	71.9	98.3	100.0	100.0	100.0	100.0	100.0	100.0
Digitized USGS % below Elev	29.7	67.9	99.7	100.0	100.0	100.0	100.0	100.0	100.0
CORPUS CHRISTI, TX AREA									
USGS Area below Elevation	14.1	25.5	42.8	68.9	90.7	109.5	157.2	157.2	157.2
USGS % below Elevation	20.5	37.0	62.1	100.0	100.0	100.0	100.0	100.0	100.0
Digitized USGS % below Elev	33.1	44.0	89.7	94.6	97.0	97.1	97.4	97.4	100.0
NEW YORK, NY AREA									
USGS Area below Elevation	-	78.1	-	122.7	-	148.8	148.8	148.8	178.5
USGS % below Elevation	-	52.5	-	82.5	-	100.0	100.0	100.0	100.0
Digitized USGS % below Elev	23.0	31.4	87.8	89.1	90.1	90.2	90.5	90.5	100.0
SAN FRANCISCO, CA AREA									
USGS Area below Elevation	57.7	68.1	-	83.6	-	94.4	-	-	94.4
USGS % below Elevation	61.1	72.1	-	88.5	-	100.0	100.0	100.0	100.0
Digitized USGS % below Elev	20.7	25.1	85.7	86.3	86.6	86.8	87.0	87.1	100.0

TABLE 24 AVERAGE GROUND SLOPE NEAR SHORELINE

(Based on data obtained from USGS quads)

Index Site	Area Below Given Elevation (sq mi)		Shoreline Length (mi)	Slope of Land Below Given Elevation	
	<5 ft	<10 ft		<5 ft	<10 ft
New York	-	78.14	220.7	-	0.0054
Long Beach Island	22.55	36.46	109.8	0.0046	0.0057
Dividing Creek	48.19	72.58	97.0	0.0019	0.0025
Miami	22.60	78.48	141.4	0.0059	0.0034
Corpus Christi	14.14	25.46	189.0	0.0127	0.0141
San Francisco	57.67	70.54	42.4	0.0007	0.0011

TABLE 25 AVERAGE GROUND SLOPE NEAR SHORELINE (Based on digitized USGS topo data)

Index Site	Area Below Given Elevation (sq mi) <5 ft	Area Below Given Elevation (sq mi) <10 ft	Shoreline Length (mi)	Slope of Land Below Given Elevation <5 ft	Slope of Land Below Given Elevation <10 ft
New York	43.04	58.70	333.4	0.0073	0.0108
Long Beach Island	18.73	22.59	77.4	0.0039	0.0065
Dividing Creek	46.80	64.81	122.3	0.0025	0.0036
Miami	32.91	75.24	119.4	0.0034	0.0030
Corpus Christi	26.18	34.83	130.1	0.0047	0.0071
San Francisco	17.32	20.98	175.1	0.0096	0.0158

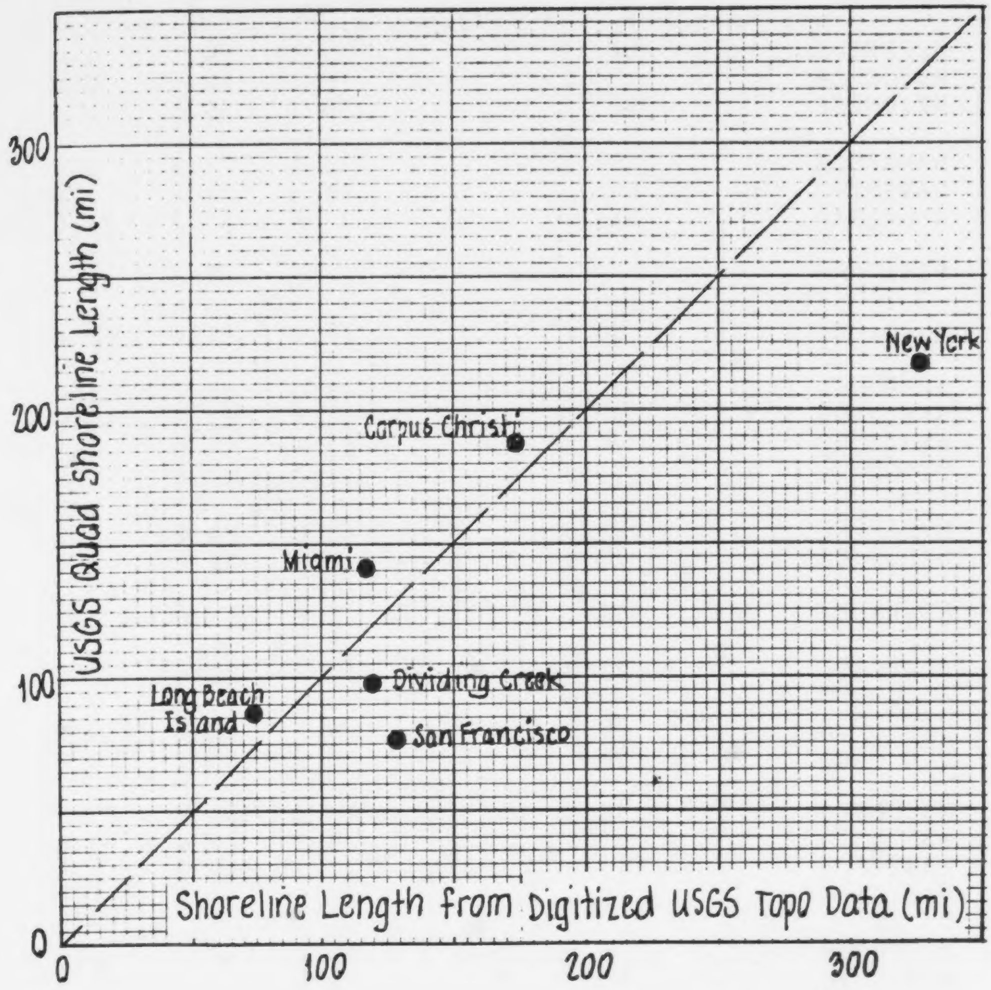


Figure 24 Correlation Between Shoreline Lengths Measured from USGS Quads and Shoreline Lengths Obtained from Digitized USGS Topographic Data.

TABLE 26 SUMMARY OF COASTAL SITE SHORELINE LENGTHS AND AREAS

	Site Abbrev.	Shoreline Length (mi)	Area (sq mi) <5 ft	<10 ft	Devel.
	MEFREEPO	141.9	22.1	24.1	1.0
	MEROCKLA	75.2	10.5	12.2	0.6
	MEJONESP	183.2	38.1	39.6	0.4
	MAMARBLE	57.2	4.1	22.3	1.5
	MAWESTPO	121.2	15.8	22.3	1.5
	MAORLEAN	144.4	37.9	42.8	24.8
	RIWATCHH	106.9	12.2	17.8	1.6
	CNBRIDGE	66.8	12.7	23.4	12.4
*	NYBROOKL	333.4	43.0	58.7	52.0
	NYNARROW	252.0	15.0	41.5	15.0
	NYPATCHO	85.3	12.6	17.0	5.1
	NYSOUTHA	134.6	11.0	20.5	2.0
*	NJDIVIDC	122.3	46.9	64.9	3.0
*	NJLONGBE	77.4	18.7	22.6	2.3
	DEREHOBA	99.1	11.0	18.9	1.2
	MDEASTON	73.2	11.0	20.8	0.5
	MDCOVEPT	9.6	0.2	0.2	0.0
	MDELKTON	53.2	4.5	6.3	0.1
	MDMIDDLE	108.1	4.9	10.2	0.2
	VACOLBEA	252.0	15.2	41.8	-
	VABLOXOM	81.5	28.9	33.4	0.0
	VANEWPOR	143.0	27.7	49.2	9.3
	VAWILTON	170.4	24.8	50.2	1.6
	NCENGELH	85.1	169.4	190.1	1.1
	NCWILMIN	150.1	32.0	44.0	27.3
	NCLONGBA	159.1	66.1	95.8	2.2
	NCCAMPLE	115.7	23.2	30.0	1.4
	SCHILTON	233.8	83.4	103.6	9.9
	SCCHARLE	164.5	74.3	109.2	12.2
	SCBROOKG	87.2	63.6	72.4	1.6
	GASEAISL	145.8	49.2	55.9	1.1

TABLE 26 (cont.) SUMMARY OF COASTAL SITE SHORELINE LENGTHS AND AREAS

	Site Abbrev.	Shoreline Length (mi)	Area (sq mi) <5 ft	Area (sq mi) <10 ft	Devel.
	FLLOSTMA	182.5	187.1	184.1	0.0
	FLCARDSO	93.9	84.8	85.5	0.1
	FLFTGADS	130.4	99.5	141.5	0.7
	FLAPALAC	96.7	21.9	34.0	1.9
*	FLMIAMI	119.4	32.9	75.2	46.3
	FLVENICE	50.2	4.2	10.1	1.9
	FLSTAUGU	91.9	26.0	41.9	5.9
	FLEVERGL	215.9	204.2	204.2	1.0
	FLCAPECA	159.1	36.8	70.2	54.4
	FLSNIPEI	51.5	37.5	72.3	0.0
	FLKEYWES	** 33.6	3.4	5.0	0.0
	FLHOLLEY	114.6	19.4	28.1	0.6
	FLFORTMY	63.1	31.6	75.1	12.3
	FLPORTRI	0.1	0.0	0.0	0.0
	FLSTJOSE	89.6	12.3	27.6	0.0
	ALGRANDI	60.3	24.3	35.0	0.6
	MSPASSCH	62.0	10.2	13.4	1.0
	MSGULFPO	29.6	6.6	11.4	1.6
	LALULING	186.7	160.4	176.4	20.0
	LABARATA	236.7	141.0	141.1	1.5
	LAGOLDME	279.6	201.1	201.1	2.2
	LABELLEC	354.3	174.6	177.3	7.9
	LACAMERO	262.8	116.1	122.3	2.1
	LAPONCHA	70.9	86.1	92.4	2.9
	LASULPHU	99.4	92.6	139.4	5.3
	LALMISER	120.7	-	212.6	2.1
	LAGRANDC	202.5	170.1	170.6	1.2
	LAPELICA	202.4	66.5	66.5	0.1
	LAMAINPA	229.0	50.8	50.8	0.0
	TXALLIGA	186.2	148.3	194.1	0.2
	TXGREENI	114.4	80.1	89.4	0.0
*	TXPORTLA	175.1	26.2	34.8	6.0
	TXPALACI	141.8	38.9	66.2	0.5
	TXRIVIER	112.0	33.5	77.2	0.0
	TXSMITHP	109.6	46.0	55.6	1.3
	TXTIVOLI	137.4	42.7	77.5	1.4

TABLE 26 (cont.) SUMMARY OF COASTAL SITE SHORELINE LENGTHS AND AREAS

	Site Abbrev.		Shoreline Length (mi)	Area (sq mi) <5 ft	<10 ft	Devel.
	CABENICI	**	358.7	52.2	56.8	6.3
	CAANONUE		57.3	3.8	4.0	0.0
	CASANQUE	**	130.1	17.3	21.0	9.0
	CAOCEANS	**	28.9	0.8	1.6	0.1
	CAPTSAL	**	27.1	0.6	0.6	0.0
*	CAPALOAL		133.6	84.6	98.7	17.8
	CAALBION		34.2	0.0	0.0	0.0
	CAFERNDA		85.9	12.5	40.0	0.8
	CATIJUAN		72.6	150.1	157.9	68.9
	CAPTMUGU		64.0	39.8	60.3	0.0
	ORPORTOR		51.0	1.5	1.93	0.3
	ORYAQUIN		109.6	0.3	0.6	0.1
	WAANACOR		105.9	6.5	7.0	0.4
	WAGARDNI		90.1	2.4	3.0	0.3
	WANEMAH		158.8	51.4	54.5	4.1
	WAPORTGA		83.8	6.6	7.6	1.7
	WATACOMA		115.7	2.5	4.0	0.7

* Denotes Index Site
** Denotes Fine Grid Data (250 m x 250 m)

CHAPTER 6

EXTRAPOLATION OF COSTS TO INCLUDE THE SHELTERED SHORELINES OF THE U.S.

A regression analysis was made using the costs of responding to sea level rise at the six index sites in order to determine the costs at 78 other coastal sites for which digitized topographic data were available (Park et al., this volume). These 84 sites comprise about 13.6% of the U.S. shoreline. The regression analysis developed equations for the amount of new bulkheading required, the amount of bulkheading that will be needed to respond to sea level rise in the years between the present and the year 2100, the number of buildings to be moved, and the number of miles of highway that would have to be raised to provide access to nearshore areas. These variables were related to topographic and development variables such as the percentage of the land below the +5-foot NGVD contour that is economically developed, and the average slope of the land below the +5-foot contour.

The percentage of the shoreline's length that is bulkheaded correlated with the percentage of the land below the +5-foot contour that is economically developed and with the average land slope below the +5-foot contour (see Figure 25). For steep land slopes (SL), the slope of the line on the figure (S1) is lower. For flatter nearshore slopes (lower SL), S1 is greater. (The slope of the land is defined here as the +5-foot 'elevation divided by the average distance between the +5-foot contour and the shoreline. The average distance of the +5-foot contour from the shoreline is equal to the land area below +5 feet divided by the shoreline length.) Similarly, the length of bulkheading to be raised in response to sea level rise was also related to the percentage of land below +5 feet that is economically developed and the average land slope (see Figure 26). Again, the slopes of the lines on the figure (S2) were found to be a function of the land slope below the +5-foot contour (SL). The relationship between the slopes of the lines on Figures 25 and 26 and the nearshore land slope is shown in Figure 27. The slopes of the lines on the figures vary almost linearly with SL. The equation is,

$$B\% = S1\ (\%AD5) \qquad (12)$$

in which B% is the percentage of the shoreline that is presently bulkheaded, S1 is the slope of the line in Figure 25 and %AD5 is the percentage of land below the +5 foot contour that is economically developed. Similarly,

$$R\% = S2\ (\%AD5) \qquad (13)$$

in which R% is the percentage of the shoreline length that will be bulkheaded by the year 2100 due to sea level rise, i.e., the amount of bulkheading that will have to be raised in order to provide continued protection because of rising sea level. S2 is the slope of the lines in Figure 26. The slopes S1 and S2 are related to the land slope near shore by the relationships,

$$S1 = -146.8\ SL + 1.85 \qquad (14)$$

and

$$S2 = -167.6\ SL + 2.20 \qquad (15)$$

See Figure 27. The length of new bulkheading that will be needed is simply the amount that will eventually be needed (the amount that would have to be raised), R%, minus the amount that is presently there, B%.

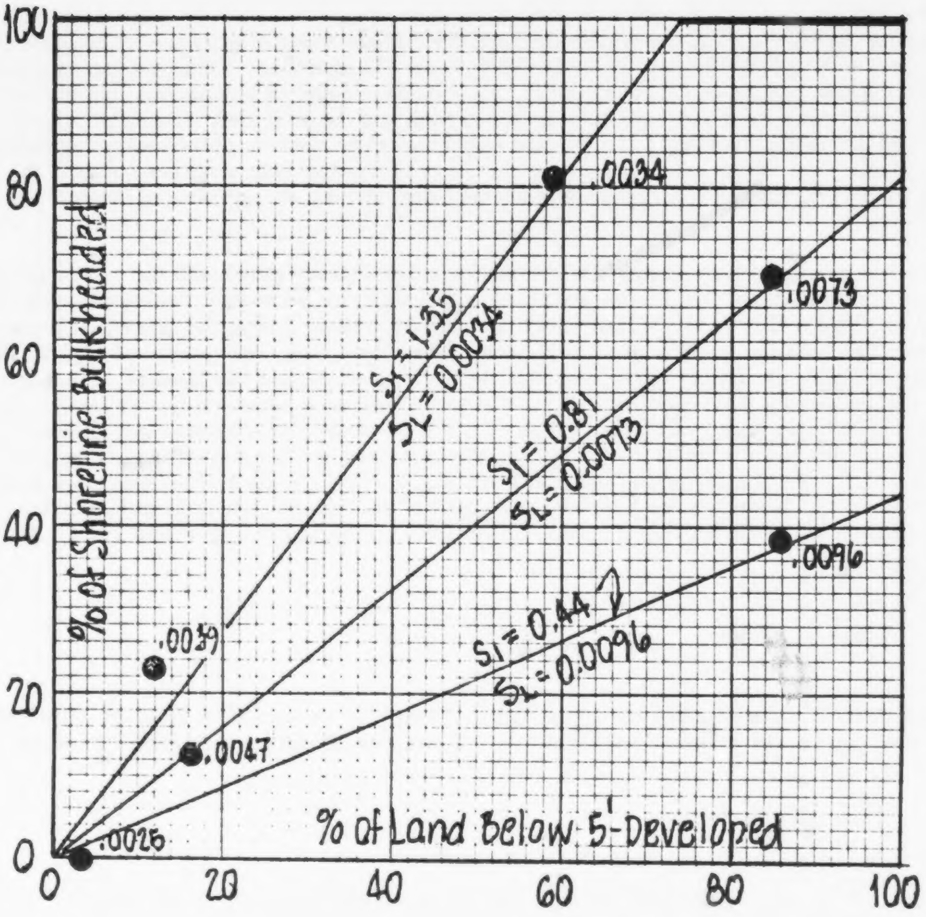


Figure 25 Correlation Between % of Shoreline Bulkheaded and % of Land Below +5 feet that is Developed and Slope of Land Near Shore.

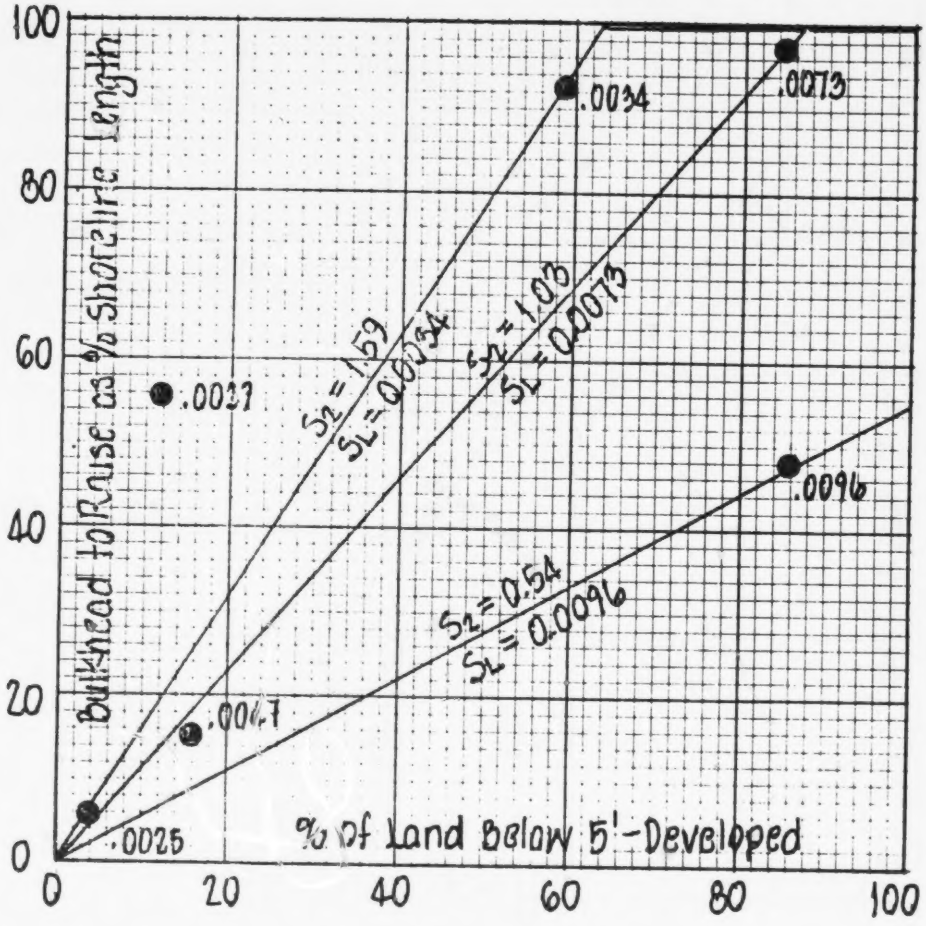


Figure 26 Correlation Between Amount of Bulkheading to be Raised as a % of Shoreline Length and % of Land Below +5 feet that is Developed and Slope of Land Near Shore.

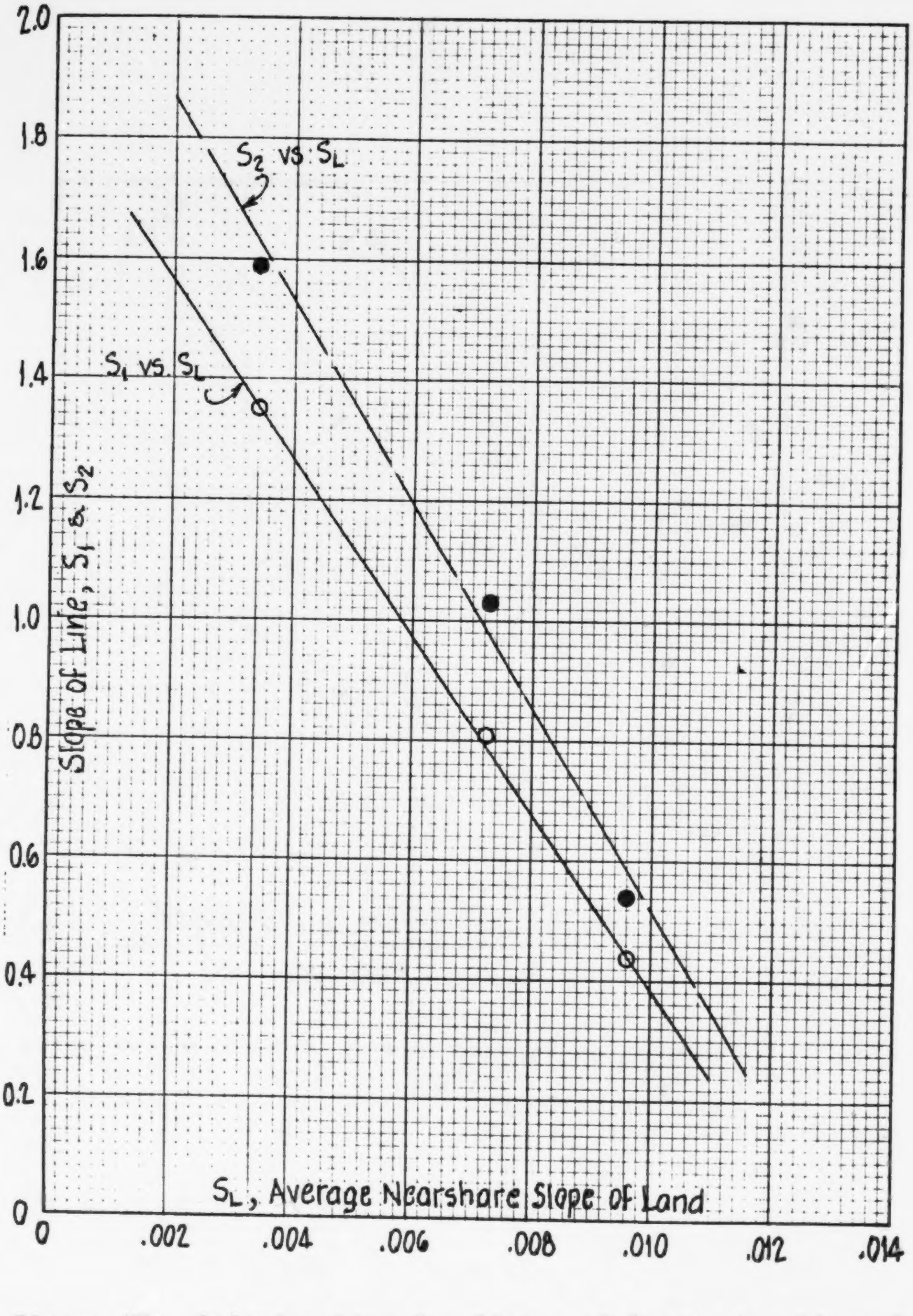


Figure 27 Relationships for Slopes of Regression Lines for Bulkheading Variables and Slope of Land Near Shore.

The number of houses that are candidates for moving was related to the percent of the shoreline that is presently bulkheaded by the relationship shown in Figure 28. The number of houses is given by,

$$N = 0.04762\,B\%^2 - 9.762\,B\% + 500 \quad (16)$$

N can be determined by first determining B% from equation 12 and then using equation 16.

No satisfactory expression could be established to determine the number of miles of highways that would have to be raised or relocated. To estimate the costs of highway relocation, the number of miles was simply expressed as a fraction of the developed land area below +5 feet in elevation. Thus,

$$LH = 0.45\,AD5 \qquad (17)$$

in which LH is the length, in miles, of highways that have to be replaced and AD5 is the area, in square miles, of developed land below +5 feet in elevation.

Costs were estimated for constructing new bulkheads, for periodically raising the existing and new bulkheads, for moving houses, and for raising/relocating highways in low-lying areas. Costs were estimated in the same way as they were estimated for the index sites. The results of the analysis are given in Table 27.

The numbers in parentheses in Table 27 are the numbers of miles of new and total bulkheading, the number of buildings to be moved, and the number of miles of highways to be raised or relocated, respectively. For the 84 sites for which shoreline lengths and developed areas were determined, the total cost of responding to sea level rise is about $3.36 billion. This is the low estimate with the cost of bulkheading/diking at $130.00 per foot. If this cost is increased to $500.00 per foot, the cost of responding to sea level rise increases to $10.8 billion (see Table 28). Since these 84 sites represent 13.6 of the U.S. sheltered shorelines, the low estimate for the entire U.S. shoreline is $24.6 billion, while the high estimate is $80.2 billion. These figures are obviously biased because of the characteristics of the 84 coastal sites on which the extrapolation is based. The sites favor the rural, little-developed southeastern U.S. coastal regions while ignoring the heavily developed Northeastern States and the Pacific Northwest. While several heavily developed areas such as the New York metropolitan area, the Miami/Miami Beach area, and the San Francisco Bay area have been included in the present analysis, a more representative sample of coastal sites would probably provide significantly higher cost estimates. The costs are summarized by coastal region in Table 29.

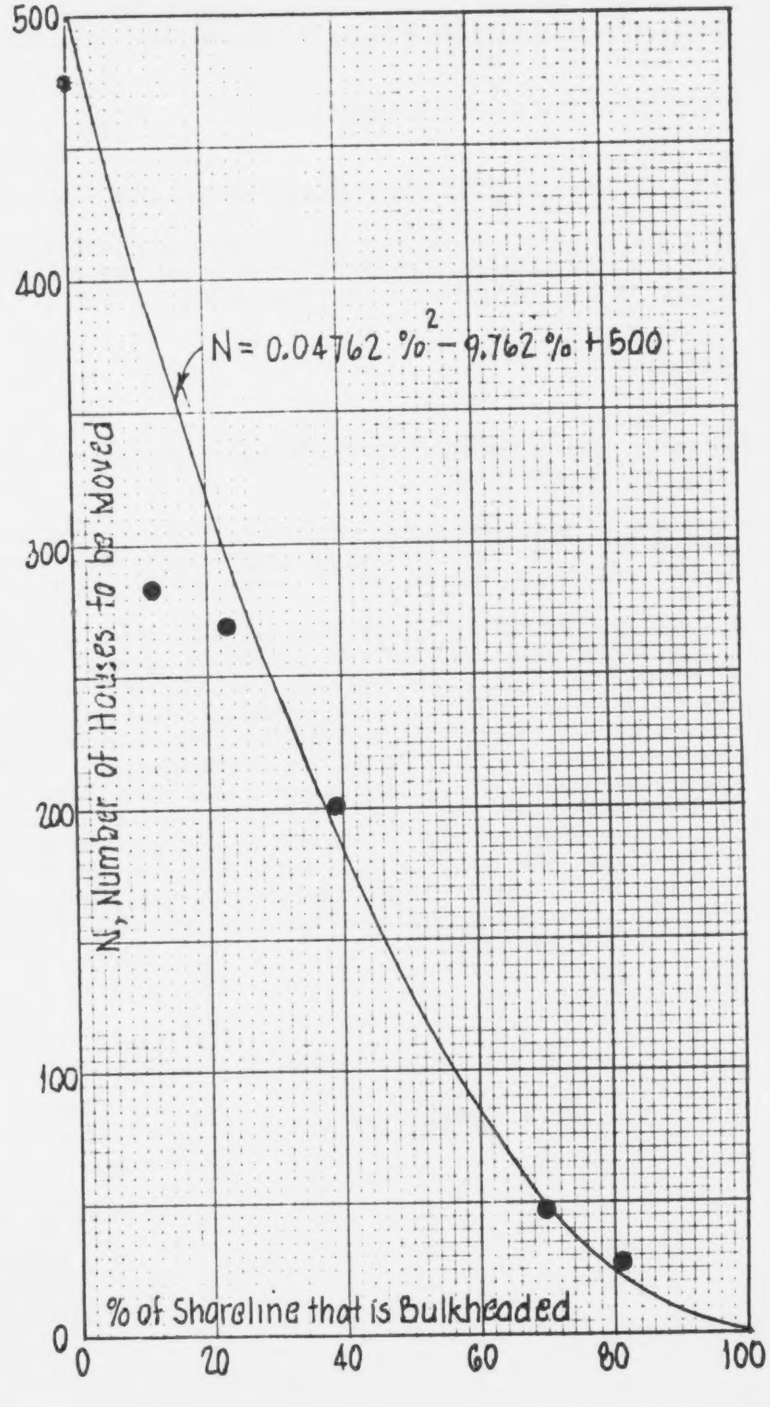


Figure 28 Relationship for Number of Houses to be Moved as a Function of the % of Shoreline that is Bulkheaded.

TABLE 27 THE COST OF SEA LEVEL RISE AT 84 SITES ALONG THE U.S. COASTLINE - LOW ESTIMATE

Site	Cost of New Bulkheads	Cost to Raise Bulkheads	Cost to Move Buildings	Cost to Replace Highways	Total Cost
MEFREEPO	$ 4.09	$ 6.99	$ 4.60	$ 1.11	$ 16.79
	(5.96 mi)	(7.36 mi)	(460)	(0.44 mi)	
MEROCKLA	$ 2.44	$ 4.20	$ 4.55	$ 0.66	$ 11.85
	(3.55 mi)	(4.42 mi)	(455)	(0.26 mi)	
MEJONESP	$ 1.60	$ 2.69	$ 4.88	$ 0.47	$ 9.64
	(2.33 mi)	(2.83 mi)	(488)	(0.18 mi)	
MAMARBLE	$ 0.00	$ 0.00	$ 5.00	$ 2.20	$ 7.20
	(0.00 mi)	(0.00 mi)	(500)	(0.87 mi)	
MAWESTPO	$ 5.99	$ 10.40	$ 4.32	$ 1.65	$ 22.36
	(8.72 mi)	(10.93 mi)	(432)	(0.65 mi)	
MAORLEAN	$ 85.61	$ 137.26	$ 0.12	$ 28.30	$ 251.28
	(124.72 mi)	(144.35 mi)	(12)	(11.16 mi)	
RIWATCHH	$ 6.22	$ 11.04	$ 4.21	$ 1.87	$ 23.33
	(9.06 mi)	(11.61 mi)	(421)	(0.74 mi)	
CNBRIDGE	$ 45.88	$ 63.56	$ 0.00	$ 14.10	$ 123.53
	(66.84 mi)	(66.84 mi)	(0)	(5.56 mi)	
NYBROOKL	$ 156.07	$ 271.45	$ 0.56	$ 43.32	$ 471.39
	(227.38 mi)	(285.47 mi)	(56)	(17.09 mi)	
NYNARROW	$ 0.00	$ 0.00	$ 5.00	$ 17.08	$ 22.08
	(0.00 mi)	(0.00 mi)	(500)	(6.74 mi)	
NYPATCHO	$ 21.54	$ 36.95	$ 2.05	$ 5.82	$ 66.36
	(31.38 mi)	(38.86 mi)	(205)	(2.29 mi)	
NYSOUTHA	$ 0.00	$ 0.00	$ 5.00	$ 2.32	$ 7.32
	(0.00 mi)	(0.00 mi)	(500)	(0.91 mi)	
NJDIVIDC	$ 4.39	$ 7.31	$ 4.50	$ 1.88	$ 18.08
	(6.40 mi)	(7.69 mi)	(450)	(0.74 mi)	
NJLONGBE	$ 8.04	$ 13.48	$ 3.63	$ 2.53	$ 27.68
	(11.71 mi)	(14.18 mi)	(363)	(1.00 mi)	

TABLE 27 (cont.) THE COST OF SEA LEVEL RISE AT 84 SITES ALONG THE U.S. COASTLINE - LOW ESTIMATE

Site	Cost of New Bulkheads	Cost to Raise Bulkheads	Cost to Move Buildings	Cost to Replace Highways	Total Cost
DEREHOBA	$ 4.29 (6.25 mi)	$ 7.66 (8.05 mi)	$ 4.40 (440)	$ 1.32 (0.52 mi)	$ 17.67
MDEASTON	$ 2.03 (2.95 mi)	$ 3.47 (3.65 mi)	$ 4.61 (461)	$ 0.55 (0.22 mi)	$ 10.66
MDCOVEPT	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
MDELKTON	$ 0.18 (0.26 mi)	$ 0.38 (0.40 mi)	$ 4.95 (495)	$ 0.11 (0.05 mi)	$ 5.63
MDMIDDLE	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.22 (0.09 mi)	$ 5.22
VACOLBEA	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.78 (0.31 mi)	$ 5.78
VABLOXOM	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
VANEWPOR	$ 37.15 (54.13 mi)	$ 62.75 (66.00 mi)	$ 1.99 (199)	$ 10.56 (4.17 mi)	$ 112.46
VAWILTON	$ 6.54 (9.53 mi)	$ 11.24 (11.82 mi)	$ 4.47 (447)	$ 1.77 (0.70 mi)	$ 24.01
NCENGELH	$ 0.42 (0.61 mi)	$ 0.69 (0.72 mi)	$ 4.93 (493)	$ 0.78 (0.31 mi)	$ 6.81
NCWILMIN	$ 75.52 (110.02 mi)	$ 127.11 (133.68 mi)	$ 0.40 (40)	$ 22.33 (8.81 mi)	$ 225.36
NCLONGBA	$ 3.15 (4.60 mi)	$ 5.24 (5.51 mi)	$ 4.72 (472)	$ 1.44 (0.57 mi)	$ 14.56
NCCAMPLE	$ 3.05 (4.44 mi)	$ 5.14 (5.41 mi)	$ 4.63 (463)	$ 0.88 (0.35 mi)	$ 13.70
SCHILTON	$ 24.70 (35.98 mi)	$ 41.12 (43.25 mi)	$ 3.61 (361)	$ 10.02 (3.96 mi)	$ 79.46

TABLE 27 (cont.) THE COST OF SEA LEVEL RISE AT 84 SITES ALONG THE U.S. COASTLINE - LOW ESTIMATE

Site	Cost of New Bulkheads	Cost to Raise Bulkheads	Cost to Move Buildings	Cost to Replace Highways	Total Cost
SCCAHRLE	$ 21.96 (31.99 mi)	$ 36.47 (38.35 mi)	$ 3.28 (328)	$ 10.69 (4.22 mi)	$ 72.39
SCBROOKG	$ 2.56 (3.73 mi)	$ 4.24 (4.46 mi)	$ 4.59 (459)	$ 1.87 (0.74 mi)	$ 13.26
GASEAISL	$ 2.84 (4.13 mi)	$ 4.73 (4.97 mi)	$ 4.73 (473)	$ 1.11 (0.44 mi)	$ 13.40
FLCARDSO	$ 0.13 (0.19 mi)	$ 0.21 (0.22 mi)	$ 4.98 (498)	$ 0.11 (0.05 mi)	$ 5.44
FLLOSTMA	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
FLFTGADS	$ 0.74 (1.07 mi)	$ 1.22 (1.28 mi)	$ 4.92 (492)	$ 0.56 (0.22 mi)	$ 7.43
FLAPALAC	$ 2.88 (4.20 mi)	$ 4.85 (5.10 mi)	$ 4.58 (458)	$ 0.88 (0.35 mi)	$ 13.19
FLMIAMI	$ 65.02 (94.73 mi)	$ 108.72 (114.34 mi)	$ 0.25 (25)	$ 22.13 (8.73 mi)	$ 196.12
FLVENICE	$ 1.21 (1.76 mi)	$ 2.69 (2.82 mi)	$ 4.66 (466)	$ 0.89 (0.35 mi)	$ 9.45
FLSTAUGU	$ 11.14 (16.23 mi)	$ 18.62 (19.58 mi)	$ 3.42 (342)	$ 3.85 (1.52 mi)	$ 37.04
FLEVERGL	$ 1.20 (1.75 mi)	$ 1.98 (2.08 mi)	$ 4.92 (492)	$ 1.11 (0.44 mi)	$ 9.21
FLCAPECA	$ 93.40 (136.08 mi)	$ 151.28 (159.10 mi)	$ 0.13 (13)	$ 28.74 (11.34 mi)	$ 273.56
FLSNIPEI	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
FLKEYWES	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00

TABLE 27 (cont.) THE COST OF SEA LEVEL RISE AT 84 SITES ALONG THE U.S. COASTLINE - LOW ESTIMATE

Site	Cost of New Bulkheads	Cost to Raise Bulkheads	Cost to Move Buildings	Cost to Replace Highways	Total Cost
FLHOLLEY	$ 2.42 (3.52 mi)	$ 4.11 (4.33 mi)	$ 4.70 (470)	$ 0.66 (0.26 mi)	$ 11.90
FLFORTMY	$ 26.44 (38.52 mi)	$ 43.86 (46.13 mi)	$ 0.81 (81)	$ 13.98 (5.52 mi)	$ 85.10
FLPORTRI	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
FLSTJOSE	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
ALGRAND	$ 1.51 (2.20 mi)	$ 2.51 (2.64 mi)	$ 4.65 (465)	$ 0.67 (0.27 mi)	$ 9.35
MSPASSCH	$ 2.01 (2.93 mi)	$ 3.43 (3.60 mi)	$ 4.55 (455)	$ 0.55 (0.22 mi)	$ 10.54
MSGULFPO	$ 2.95 (4.29 mi)	$ 4.95 (5.21 mi)	$ 3.69 (369)	$ 0.89 (0.35 mi)	$ 12.47
LALULING	$ 19.53 (28.45 mi)	$ 32.30 (33.97 mi)	$ 3.62 (362)	$ 16.51 (6.52 mi)	$ 71.96
LABARATA	$ 2.87 (4.18 mi)	$ 4.75 (5.00 mi)	$ 4.83 (483)	$ 1.76 (0.69 mi)	$ 14.21
LAGOLDME	$ 3.51 (5.11 mi)	$ 5.81 (6.11 mi)	$ 4.82 (482)	$ 2.53 (1.00 mi)	$ 16.67
LAGRANDC	$ 1.60 (2.33 mi)	$ 2.64 (2.78 mi)	$ 4.89 (489)	$ 1.32 (0.52 mi)	$ 10.45
LAPELICA	$ 0.30 (0.43 mi)	$ 0.50 (0.52 mi)	$ 4.98 (498)	$ 0.11 (0.05 mi)	$ 5.89
LAMAINPA	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
LABELLEC	$ 17.29 (25.20 mi)	$ 28.70 (30.18 mi)	$ 4.33 (433)	$ 9.03 (3.56 mi)	$ 59.35

TABLE 27 (cont.) THE COST OF SEA LEVEL RISE AT 84 SITES ALONG THE U.S. COASTLINE - LOW ESTIMATE

Site	Cost of New Bulkheads	Cost to Raise Bulkheads	Cost to Move Buildings	Cost to Replace Highways	Total Cost
LACAMERO	$ 5.51 (8.03 mi)	$ [illegible] (9.62 mi)	$ 4.71 (471)	$ 2.63 (1.04 mi)	$ 22.00
LAPONCHA	$ 2.85 (4.15 mi)	$ 4.70 (4.94 mi)	$ 4.45 (445)	$ 3.31 (1.31 mi)	$ 15.30
LASULPHU	$ 6.67 (9.71 mi)	$ 11.02 (11.59 mi)	$ 4.09 (409)	$ 6.07 (2.39 mi)	$ 27.85
LALMISER	$ 1.80 (2.62 mi)	$ 2.97 (3.12 mi)	$ 4.79 (479)	$ 2.43 (0.96 mi)	$ 11.98
TXALLIGA	$ 0.14 (0.21 mi)	$ 0.24 (0.25 mi)	$ 4.99 (499)	$ 0.11 (0.05 mi)	$ 5.49
TXGREENI	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
TXPORTLA	$ 18.33 (26.71 mi)	$ 31.42 (33.05 mi)	$ 3.62 (362)	$ 4.95 (1.95 mi)	$ 58.33
TXPALACI	$ 1.65 (2.40 mi)	$ 2.75 (2.90 mi)	$ 4.84 (484)	$ 0.56 (0.22 mi)	$ 9.80
TXRIVIER	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
TXSMITHP	$ 3.13 (4.56 mi)	$ 5.20 (5.47 mi)	$ 4.60 (460)	$ 1.44 (0.57 mi)	$ 14.37
TXTIVOLI	$ 4.22 (6.14 mi)	$ 7.03 (7.40 mi)	$ 4.57 (457)	$ 1.55 (0.61 mi)	$ 17.37
CABENICI	$ 22.70 (33.08 mi)	$ 39.00 (41.01 mi)	$ 4.14 (414)	$ 6.14 (2.42 mi)	$ 71.98
CAANONUE	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
CASANQUE	$ 31.73 (46.23 mi)	$ 54.98 (57.83 mi)	$ 2.13 (213)	$ 8.71 (3.44 mi)	$ 97.56

TABLE 27 (cont.) THE COST OF SEA LEVEL RISE AT 84 SITES ALONG THE U.S. COASTLINE - LOW ESTIMATE

Site	Cost of New Bulkheads	Cost to Raise Bulkheads	Cost to Move Buildings	Cost to Replace Highways	Total Cost
CAOCEANS	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.08 (0.03 mi)	$ 5.08
CAPTSAL	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
CAPALOAL	$ 26.46 (38.55 mi)	$ 43.82 (46.08 mi)	$ 2.58 (258)	$ 17.07 (6.74 mi)	$ 89.93
CAALBION	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
CAFERNDA	$ 3.25 (4.73 mi)	$ 5.58 (5.87 mi)	$ 4.48 (448)	$ 0.88 (0.35 mi)	$ 14.19
CATIJUAN	$ 40.81 (59.46 mi)	$ 67.34 (70.82 mi)	$ 0.20 (20)	$ 78.60 (31.01 mi)	$ 186.95
CAPTMAGU	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
ORPORTOR	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.33 (0.13 mi)	$ 5.33
ORYAQUIN	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.11 (0.05 mi)	$ 5.11
WAANACOR	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.44 (0.18 mi)	$ 5.44
WAGARDNI	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.33 (0.13 mi)	$ 5.33
WANEMAH	$ 12.19 (17.77 mi)	$ 20.33 (21.38 mi)	$ 3.97 (397)	$ 4.62 (1.82 mi)	$ 41.11
WAPORTGA	$ 1.12 (1.63 mi)	$ 3.63 (3.82 mi)	$ 4.81 (481)	$ 1.98 (0.78 mi)	$ 11.54
WATACOMA	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.78 (0.31 mi)	$ 5.78

TABLE 28 THE COST OF SEA LEVEL RISE AT 84 SITES ALONG THE U.S. COASTLINE - HIGH ESTIMATE

Site	Cost of New Bulkheads	Cost to Raise Bulkheads	Cost to Move Buildings	Cost to Replace Highways	Total Cost
MEFREEPO	$ 15.74 (5.96 mi)	$ 26.89 (7.36 mi)	$ 4.60 (460)	$ 1.48 (0.44 mi)	$ 48.71
MEROCKLA	$ 9.37 (3.55 mi)	$ 16.15 (4.42 mi)	$ 4.55 (455)	$ 0.88 (0.26 mi)	$ 30.96
MEJONESP	$ 6.15 (2.33 mi)	$ 10.36 (2.83 mi)	$ 4.88 (488)	$ 0.62 (0.18 mi)	$ 22.01
MAMARBLE	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 2.93 (0.87 mi)	$ 7.93
MAWESTPO	$ 23.03 (8.72 mi)	$ 39.99 (10.93 mi)	$ 4.32 (432)	$ 2.20 (0.65 mi)	$ 69.54
MAORLEAN	$ 329.27 (124.72 mi)	$ 527.91 (144.35 mi)	$ 0.12 (12)	$ 37.73 (11.16 mi)	$ 895.02
RIWATCHH	$ 23.91 (9.06 mi)	$ 42.44 (11.61 mi)	$ 4.21 (421)	$ 2.49 (0.74 mi)	$ 73.05
CNBRIDGE	$ 176.46 (66.84 mi)	$ 244.44 (66.84 mi)	$ 0.00 (0)	$ 18.80 (5.56 mi)	$ 439.70
NYBROOKL	$ 600.28 (227.38 mi)	$ 1044.02 (285.47 mi)	$ 0.56 (56)	$ 57.75 (17.09 mi)	$ 1702.61
NYNARROW	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 22.78 (6.74 mi)	$ 27.78
NYPATCHO	$ 82.85 (31.38 mi)	$ 142.11 (38.86 mi)	$ 2.05 (205)	$ 7.76 (2.29 mi)	$ 234.77
NYSOUTHA	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 3.09 (0.91 mi)	$ 8.09
NJDIVIDC	$ 16.90 (6.40 mi)	$ 28.11 (7.69 mi)	$ 4.50 (450)	$ 2.51 (0.74 mi)	$ 52.01
NJLONGBE	$ 30.92 (11.71 mi)	$ 51.85 (14.18 mi)	$ 3.63 (363)	$ 3.38 (1.00 mi)	$ 89.78

TABLE 28 (cont.) THE COST OF SEA LEVEL RISE AT 84 SITES ALONG THE U.S. COASTLINE - HIGH ESTIMATE

Site	Cost of New Bulkheads	Cost to Raise Bulkheads	Cost to Move Buildings	Cost to Replace Highways	Total Cost
DEREHOBA	$ 16.49 (6.25 mi)	$ 29.44 (8.05 mi)	$ 4.40 (440)	$ 1.76 (0.52 mi)	$ 52.11
MDEASTON	$ 7.80 (2.95 mi)	$ 13.36 (3.65 mi)	$ 4.61 (461)	$ 0.73 (0.22 mi)	$ 26.50
MDCOVEPT	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
MDELKTON	$ 0.69 (0.26 mi)	$ 1.46 (0.40 mi)	$ 4.95 (495)	$ 0.15 (0.05 mi)	$ 7.25
MDMIDDLE	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.29 (0.09 mi)	$ 5.29
VACOLBEA	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 1.03 (0.31 mi)	$ 6.03
VABLOXOM	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
VANEWPOR	$ 142.90 (54.13 mi)	$ 241.36 (66.00 mi)	$ 1.99 (199)	$ 14.08 (4.17 mi)	$ 400.33
VAWILTON	$ 25.16 (9.53 mi)	$ 43.21 (11.82 mi)	$ 4.47 (447)	$ 2.36 (0.70 mi)	$ 75.20
NCENGELH	$ 1.61 (0.61 mi)	$ 2.65 (0.72 mi)	$ 4.93 (493)	$ 1.03 (0.31 mi)	$ 10.22
NCWILMIN	$ 290.46 (110.02 mi)	$ 488.89 (133.68 mi)	$ 0.40 (40)	$ 29.77 (8.81 mi)	$ 809.52
NCLONGBA	$ 12.13 (4.60 mi)	$ 20.16 (5.51 mi)	$ 4.72 (472)	$ 1.92 (0.57 mi)	$ 38.93
NCCAMPLE	$ 11.73 (4.44 mi)	$ 19.78 (5.41 mi)	$ 4.63 (463)	$ 1.17 (0.35 mi)	$ 37.31
SCHILTON	$ 95.00 (35.98 mi)	$ 158.16 (43.25 mi)	$ 3.61 (361)	$ 13.37 (3.96 mi)	$ 270.14

TABLE 28 (cont.) THE COST OF SEA LEVEL RISE AT 84 SITES ALONG THE U.S. COASTLINE - HIGH ESTIMATE

Site	Cost of New Bulkheads	Cost to Raise Bulkheads	Cost to Move Buildings	Cost to Replace Highways	Total Cost
SCCAHRLE	$ 84.46 (31.99 mi)	$ 140.25 (38.35 mi)	$ 3.28 (328)	$ 14.25 (4.22 mi)	$ 242.24
SCBROOKG	$ 9.85 (3.73 mi)	$ 16.30 (4.46 mi)	$ 4.59 (459)	$ 2.49 (0.74 mi)	$ 33.23
GASEAISL	$ 10.91 (4.13 mi)	$ 18.18 (4.97 mi)	$ 4.73 (473)	$ 1.48 (0.44 mi)	$ 35.30
FLCARDSO	$ 0.50 (0.19 mi)	$ 0.82 (0.22 mi)	$ 4.98 (498)	$ 0.15 (0.05 mi)	$ 6.45
FLLOSTMA	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
FLFTGADS	$ 2.83 (1.07 mi)	$ 4.68 (1.28 mi)	$ 4.92 (492)	$ 0.75 (0.22 mi)	$ 13.17
FLAPALAC	$ 11.10 (4.20 mi)	$ 18.64 (5.10 mi)	$ 4.58 (458)	$ 1.17 (0.35 mi)	$ 35.49
FLMIAMI	$ 250.09 (94.73 mi)	$ 418.16 (114.34 mi)	$ 0.25 (25)	$ 29.50 (8.73 mi)	$ 698.00
FLVENICE	$ 4.64 (1.76 mi)	$ 10.33 (2.82 mi)	$ 4.66 (466)	$ 1.19 (0.35 mi)	$ 20.82
FLSTAUGU	$ 42.85 (16.23 mi)	$ 71.61 (19.58 mi)	$ 3.42 (342)	$ 5.14 (1.52 mi)	$ 123.03
FLEVERGL	$ 4.61 (1.75 mi)	$ 7.62 (2.08 mi)	$ 4.92 (492)	$ 1.48 (0.44 mi)	$ 18.63
FLCAPECA	$ 359.24 (136.08 mi)	$ 581.85 (159.10 mi)	$ 0.13 (13)	$ 38.32 (11.34 mi)	$ 979.54
FLSNIPEI	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
FLKEYWES	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00

TABLE 28 (cont.) THE COST OF SEA LEVEL RISE AT 84 SITES ALONG THE U.S. COASTLINE - HIGH ESTIMATE

Site	Cost of New Bulkheads	Cost to Raise Bulkheads	Cost to Move Buildings	Cost to Replace Highways	Total Cost
FLHOLLEY	$ 9.31 (3.52 mi)	$ 15.82 (4.33 mi)	$ 4.70 (470)	$ 0.88 (0.26 mi)	$ 30.71
FLFORTMY	$ 101.69 (38.52 mi)	$ 168.71 (46.13 mi)	$ 0.81 (81)	$ 18.64 (5.52 mi)	$ 289.85
FLPORTRI	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
FLSTJOSE	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
ALGRAND	$ 5.81 (2.20 mi)	$ 9.66 (2.64 mi)	$ 4.65 (465)	$ 0.90 (0.27 mi)	$ 21.03
MSPASSCH	$ 7.74 (2.93 mi)	$ 13.18 (3.60 mi)	$ 4.55 (455)	$ 0.73 (0.22 mi)	$ 26.20
MSGULFPO	$ 11.33 (4.29 mi)	$ 19.04 (5.21 mi)	$ 3.69 (369)	$ 1.19 (0.35 mi)	$ 35.24
LALULING	$ 75.12 (28.45 mi)	$ 124.22 (33.97 mi)	$ 3.62 (362)	$ 22.02 (6.52 mi)	$ 224.98
LABARATA	$ 11.03 (4.18 mi)	$ 18.28 (5.00 mi)	$ 4.83 (483)	$ 2.34 (0.69 mi)	$ 36.49
LAGOLDME	$ 13.50 (5.11 mi)	$ 22.34 (6.11 mi)	$ 4.82 (482)	$ 3.38 (1.00 mi)	$ 44.04
LAGRANDC	$ 6.14 (2.33 mi)	$ 10.16 (2.78 mi)	$ 4.89 (489)	$ 1.76 (0.52 mi)	$ 22.95
LAPELICA	$ 1.15 (0.43 mi)	$ 1.91 (0.52 mi)	$ 4.98 (498)	$ 0.15 (0.05 mi)	$ 8.19
LAMAINPA	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
LABELLEC	$ 66.52 (25.20 mi)	$ 110.37 (30.18 mi)	$ 4.33 (433)	$ 12.04 (3.56 mi)	$ 193.26

TABLE 28 (cont.) THE COST OF SEA LEVEL RISE AT 84 SITES ALONG THE U.S. COASTLINE - HIGH ESTIMATE

Site	Cost of New Bulkheads	Cost to Raise Bulkheads	Cost to Move Buildings	Cost to Replace Highways	Total Cost
LACAMERO	$ 21.19	$ 35.19	$ 4.71	$ 3.51	$ 64.60
	(8.03 mi)	(9.62 mi)	(471)	(1.04 mi)	
LAPONCHA	$ 10.94	$ 18.08	$ 4.45	$ 4.41	$ 37.88
	(4.15 mi)	(4.94 mi)	(445)	(1.31 mi)	
LASULPHU	$ 25.64	$ 42.39	$ 4.09	$ 8.09	$ 80.21
	(9.71 mi)	(11.59 mi)	(409)	(2.39 mi)	
LALMISER	$ 6.91	$ 11.41	$ 4.79	$ 3.24	$ 26.34
	(2.62 mi)	(3.12 mi)	(479)	(0.96 mi)	
TXALLIGA	$ 0.56	$ 0.92	$ 4.99	$ 0.15	$ 6.62
	(0.21 mi)	(0.25 mi)	(499)	(0.05 mi)	
TXGREENI	$ 0.00	$ 0.00	$ 5.00	$ 0.00	$ 5.00
	(0.00 mi)	(0.00 mi)	(500)	(0.00 mi)	
TXPORTLA	$ 70.52	$ 120.85	$ 3.62	$ 6.60	$ 201.59
	(26.71 mi)	(33.05 mi)	(362)	(1.95 mi)	
TXPALACI	$ 6.33	$ 10.59	$ 4.84	$ 0.75	$ 22.51
	(2.40 mi)	(2.90 mi)	(484)	(0.22 mi)	
TXRIVIER	$ 0.00	$ 0.00	$ 5.00	$ 0.00	$ 5.00
	(0.00 mi)	(0.00 mi)	(500)	(0.00 mi)	
TXSMITHP	$ 12.03	$ 19.99	$ 4.60	$ 1.92	$ 38.54
	(4.56 mi)	(5.47 mi)	(460)	(0.57 mi)	
TXTIVOLI	$ 16.21	$ 27.05	$ 4.57	$ 2.07	$ 49.91
	(6.14 mi)	(7.40 mi)	(457)	(0.61 mi)	
CABENICI	$ 87.33	$ 149.99	$ 4.14	$ 8.18	$ 249.64
	(33.08 mi)	(41.01 mi)	(414)	(2.42 mi)	
CAANONUE	$ 0.00	$ 0.00	$ 5.00	$ 0.00	$ 5.00
	(0.00 mi)	(0.00 mi)	(500)	(0.00 mi)	
CASANQUE	$ 122.04	$ 211.47	$ 2.13	$ 11.62	$ 347.26
	(46.23 mi)	(57.83 mi)	(213)	(3.44 mi)	

TABLE 28 (cont.) THE COST OF SEA LEVEL RISE AT 84 SITES ALONG THE U.S. COASTLINE - HIGH ESTIMATE

Site	Cost of New Bulkheads	Cost to Raise Bulkheads	Cost to Move Buildings	Cost to Replace Highways	Total Cost
CAOCEANS	$ 0.00	$ 0.00	$ 5.00	$ 0.11	$ 5.11
	(0.00 mi)	(0.00 mi)	(500)	(0.03 mi)	
CAPTSAL	$ 0.00	$ 0.00	$ 5.00	$ 0.00	$ 5.00
	(0.00 mi)	(0.00 mi)	(500)	(0.00 mi)	
CAPALOAL	$ 101.76	$ 168.54	$ 2.58	$ 22.76	$ 295.64
	(38.55 mi)	(46.08 mi)	(258)	(6.74 mi)	
CAALBION	$ 0.00	$ 0.00	$ 5.00	$ 0.00	$ 5.00
	(0.00 mi)	(0.00 mi)	(500)	(0.00 mi)	
CAFERNDA	$ 12.49	$ 21.47	$ 4.48	$ 1.17	$ 39.61
	(4.73 mi)	(5.87 mi)	(448)	(0.35 mi)	
CATIJUAN	$ 156.97	$ 258.98	$ 0.20	$ 104.80	$ 520.96
	(59.46 mi)	(70.82 mi)	(20)	(31.01 mi)	
CAPTMAGU	$ 0.00	$ 0.00	$ 5.00	$ 0.00	$ 5.00
	(0.00 mi)	(0.00 mi)	(500)	(0.00 mi)	
ORPORTOR	$ 0.00	$ 0.00	$ 5.00	$ 0.44	$ 5.44
	(0.00 mi)	(0.00 mi)	(500)	(0.13 mi)	
ORYAQUIN	$ 0.00	$ 0.00	$ 5.00	$ 0.15	$ 5.15
	(0.00 mi)	(0.00 mi)	(500)	(0.05 mi)	
WAANACOR	$ 0.00	$ 0.00	$ 5.00	$ 0.59	$ 5.59
	(0.00 mi)	(0.00 mi)	(500)	(0.18 mi)	
WAGARDNI	$ 0.00	$ 0.00	$ 5.00	$ 0.44	$ 5.44
	(0.00 mi)	(0.00 mi)	(500)	(0.13 mi)	
WANEMAH	$ 46.90	$ 78.19	$ 3.97	$ 6.16	$ 135.22
	(17.77 mi)	(21.38 mi)	(397)	(1.82 mi)	
WAPORTGA	$ 4.30	$ 13.95	$ 4.81	$ 2.65	$ 25.72
	(1.63 mi)	(3.82 mi)	(481)	(0.78 mi)	
WATACOMA	$ 0.00	$ 0.00	$ 5.00	$ 1.03	$ 6.03
	(0.00 mi)	(0.00 mi)	(500)	(0.31 mi)	

TABLE 29 NATIONWIDE ESTIMATE ($ millions)

	Low	High
Northeast	6,932	23,607
Mid Atlantic	4,354	14,603
Southeast	9,249	29,883
West	4,097	12,802
USA	24,633	80,176

REFERENCES

Bruun, P. (1962). "Sea Level Rise as a Cause of Erosion," Journal of the Waterways and Harbors Division, ASCE, Vol. 88, No. WW1, February 1962, pp. 117-130.

Fairbridge, R.W. (1961). "Eustatic changes in sea level. Physics and Chemistry of the Earth, Vol. 4, pp. 99-185

Fairbridge, R.W. & O.A. Krebs (1962). Sea Level and the Southern Oscillation," Geophysical Journal, Royal Astron. Proceedings, Vol. 6, No. 4, pp. 532-545.

Gornitz, V., S. Lebedeff, & J. Hansen (1982). "Global sea level trends in the past century," Science, Vol. 215, pp. 1611-1614.

Hoffman, (1985). "Estimates of Future Sea Level Rise" in Greenhouse Effect and Sea Level Rise, M.C. Barth & J.G. Titus, editors, Van Nostrand Reinhold Co., Inc., New York, NY.

Lyle et al. (1987). "Sea Level Variations in the U.S.," National Ocean Survey, Rockville, MD, 1987.

Meier, M.F. et al. (1985). Glaciers, Ice Sheets and Sea Level, National Academy Press, 1985.

National Research Council (1987). Responding to Changes in Sea Level, Engineering Implications, Committee on Engineering Implications of Changes in Relative Mean Sea Level, Marine Board, National Academy Press Washington, DC.

Revelle, R. (1983). "Probable Future Changes in Sea Level Resulting from Increased Atmospheric Carbon Dioxide," in Changing Climate, Carbon Dioxide Assessment Committee, Washington, DC, National Academy Press, pp. 433-447.

Titus, J. (1986). "Greenhouse Effect, Sea Level Rise and Coastal Zone Management," Coastal Zone Management Journal, Vol. 14, No. 3.

Soil Conservation Service (1986). "Urban Hydrology for Small Watersheds," Technical Release No. 55, U.S. Department of Agriculture, Soil Conservation Service, June 1986.

THE COST OF NOT HOLDING BACK THE SEA - PHASE 1
ECONOMIC VULNERABILITY

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FINDINGS[1]

The first step in estimating the cost to the United States of allowing the oceans to rise in response to greenhouse warming against unprotected coastlines is to develop a methodology by which researchers can catalog and measure the current value of real sources of economic wealth that might be threatened. Such measures represent initial, if naive, estimates of the social cost that would be incurred at each site if a decision to forego any protection from rising seas were made. If the sites chosen for application of the methodology are also part of a national sample, the localized estimates that they support can eventually be used to judge the potential cost of a universally applied decision of no protection. They can, in other words, be used to produce a first cut at a measure of economic vulnerability across the United States to greenhouse-induced sea level rise.

This paper reports on the first steps of a process which will lead to this national estimate. The first three chapters are designed to outline the methodology by which site-specific cost estimates were made for Long Beach Island, New Jersey, and to record the results of its application. In the first, the underlying theory of the measurement is described. There are three areas of focus: the value of threatened structure, the value of threatened property, and, where appropriate, the social value of threatened coastline. The results of applying the theory to Long Beach Island are recorded in Chapter 2, while discussion found in the third chapter tries to put these local results into some perspective.

Broader perspective is drawn in the last two chapters. Chapter 4 begins the extension by describing more fully the sampling methodology by which local estimates of vulnerability can lead to a national estimate. The site selection process and more generally applicable estimation procedures are of particular interest there. A final chapter concludes with an outline of the issues that will have to be confronted if measures of economic vulnerability are to be translated into measures of economic cost. Discounting, uncertainty, growth, depreciation, and frictional adjustment costs will all have to be considered; identifying their precise role in the translation process certainly will be the focus of subsequent research.

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CHAPTER 1

THE THEORY BEHIND MEASURING VULNERABILITY

The cost of not holding back the sea should flow from at least four separate sources: (1) the value of lost structure, (2) the value of lost property, (3) the value of lost social "services" delivered from the existing coastline, and (4) adjustment costs associated with redeploying productive resources once applied to the lost land. The present effort considers only the first three of these sources, postponing any thorough consideration of the frictional costs of redeployment until later.[2] They relate more to immediate measures of vulnerability; the last relate more to adjustments that will be required to translate vulnerability to cost.

Land and structures are, for example, stores of economic wealth; even threatening their loss would likely produce macroeconomic reductions in aggregate demand, the effects of which would extend well beyond the shoreline. The extent of their potential contractionary influence on economic activity and long-term growth is thus another concern which should be investigated when the dimension of likely shoreline loss is more fully understood.[3] Social services provided by coastlines are, similarly, major components of economic and social well-being for which people have demonstrated a significant and immediate willingness to pay. Each of the first three sources of potential cost is, therefore, significant and deserving of individual attention.

THE VALUE OF THREATENED STRUCTURE

The precise notion employed to compute the economic value of threatened structure is that people will abandon a structure when the land upon which it sits is covered by water during mean spring high tide. In fact, the inundation scenarios upon which the vulnerability calculations are based are not sufficiently detailed to apply that notion exactly. The shoreline retreat scenarios provided by Park et al. (this volume) indicate, for each site in the national sample, only the percentages of developed cells (usually 500 meters square) that are flooded when the seas rise 50 cm, 100 cm, and 200 cm through 2100. In practice, therefore, the percentage of structure currently located in each cell and deemed abandoned with each increment of sea level rise must be taken to be the percentage of that cell that is flooded.

More precisely, the current value of structure located within any specific cell can be estimated from tax records or housing and business census data on the basis of a sample of structures presently located within its boundaries. To be sure, neither tax records nor census data necessarily reflect current market value. A reasonable translation from recorded value to current market value can, however, be accomplished by noting (1) the percentage of market value reported by the assessor's office, and (2) some degree of inflation since the last assessment. The accuracy of the translation can, in addition, be validated by comparing the assessed values of structures now on the market with their quoted prices. Moving to an estimate of the value of threatened structure within that cell can then be accomplished using the percentages indicated by the inundation scenarios.

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[2] See Chapter 5 for a brief discussion of the anticipated role of adjustment cost in the process which translates economic vulnerability to economic cost. Adequate treatment of frictional adjustment costs will involve more sophisticated intertemporal modeling.

[3] Real estate markets are assumed to be efficient, so the economic value of public goods and services which are also threatened by inundation is capitalized in the values of land and structure. No separate accounting of public goods and services is therefore necessary. No notion of critical mass is employed, as a result, so some early vulnerability estimates for regions which will essentially disappear may be too low; they will capture the total loss of the value of public activity only when the last piece of property is lost even though, in fact, public activity probably stopped years earlier.

If, for example, a 50-cm sea level rise is expected to put x% of the region under water by the year 2075, then it can be assumed that x% of the estimated value of the structure located in that region is lost by 2075. Adding across all threatened cells can finally produce a site-specific cost estimate of potential structure loss.

One sampling procedure upon which the estimation process can rest looks at strips of land running inland from the shoreline past an inland point at which (1) property and structure are no longer threatened by sea level rise, and (2) property values no longer reflect surplus location rent derived from proximity with the shore. Series of real estate valuations along these strips should be sufficient to support aggregate potential cost estimates subject, of course, to some sampling error. Sampling error could be avoided completely if the inundation scenarios were more detailed and if tax records were digitized, but neither of these conditions is met in reality. Resulting estimates must rely, instead, on the efficient operation of real estate markets to keep the sampling errors low; a small number of strips in each sample should, in fact, be sufficient to keep the t-statistics around sample means of (e.g.) structure values, in excess of 10.

The technicalities of sampling aside, a procedure which uses current value as a measure of potential future cost can be criticized for several reasons. For one thing, the sites being studied will surely enjoy economic growth over the next half century or so. Current value misses that growth entirely. For another, structure prices tend to inflate more quickly than the general Consumer Price Index. Estimates based on current value might, therefore, be conservative to the degree that they ignore either or both of these phenomena.

On the other hand, using current value sidesteps both the vagaries of social discounting and the potential that threatened structures will be allowed to fall into disrepair when it becomes known that they may be under water in the foreseeable future. Inasmuch as the cost of not holding back the sea will be compared with the cost of protection on a year-to-year (or decade-to-decade) basis as various future scenarios unfold, however, the problems created by not discounting are not necessarily as severe as they might at first appear. They may involve discounting over a decade's time, for example, and not over a half-century. Moreover, it may turn out that the growth and relative inflation trends just noted proceed over the long term at a rate which roughly offsets the effect of discounting on the real value of threatened structure. Current value and present value would then match over the long term if not over decades.

The issue of not maintaining structure is also one of timing. For example, if the owner of a $200,000 structure that will be inundated in the year 2050 were to ignore its physical upkeep over the 25-year period from the year 2025 to 2050, then the owner would suffer a smaller loss in 2050 than he would otherwise. How much smaller? The present value, in 2050, of the money that he did not spend maintaining the property since the year 2025 net of the reduced rent that he received as the property deteriorated. If, however, it were known that the structure were going to be abandoned in 2050, then the market value of that structure would begin to decline well before 2050. An accurate accounting of the economic loss might therefore also start recording this decline in value years ahead of the 2025 collapse, thereby moving the loss forward and increasing its current present value. Which effect would dominate is, at this point, anybody's guess; but it is certainly an issue which warrants further consideration.

All of these intertemporal issues will be considered, when vulnerability measures are adjusted to reflect cost, with an eye toward keeping track of precisely "Who knows what and when?" Discounting must, for example, be considered to the extent that decisions to protect ponder investment at some time certain in anticipation of avoiding loss sometime in the future. Its implications will be clear, however, only in the context of modeling, which also allows for economic growth, depreciation, market expectations, and uncertainty. For the moment, it must be emphasized that only current value estimates are provided here.

THE VALUE OF THREATENED PROPERTY

The same sampling procedure outlined above can also be used to produce estimates of the current value of lost property which are subject to virtually the same set of concerns. To the degree that current values miss the effects of higher relative inflation, they likely to be too low. To the degree that they are not discounted, they are likely to be too high. Market value erosion might also be expected; it would be based on the same rational response to anticipated inundation, and it would happen automatically through the operation of the marketplace. In fact, the only caveat that no longer applies is the analog to an owner's ability to run down a structure. The value of the land upon which something might be built cannot be significantly diminished by neglect. It may become unsightly, but the marketplace will continue to acknowledge its intrinsic value derived from location and other relatively unalterable characteristics.

There is, however, one additional wrinkle that must be considered -- exactly what piece of property is lost when the sea rises? For structures, the answer to this question is simple; the structure that is abandoned is the one that is lost. For property, though, loss of a shoreline lot means that the next lot is now a shoreline lot. Economic loss should, therefore, be measured at some interior point.

To see this more precisely, consult Figure 1; a hypothetical property value gradient for one-eighth acre lots is displayed there. Note that values start at $100,000 on the shoreline and eventually stabilize at $50,000 some 500 feet from the shoreline. Were the sea to rise so that the first lot were lost, then the second lot would become a shoreline lot and assume the $100,000 value originally attributed to the first. The value of the third lot would climb to $90,000, and so on. The community would, in effect, lose the economic value of an interior lot located initially more than 500 feet from the shoreline. The true economic loss would be the equivalent of a $50,000 lot instead of the shoreline $100,000 lot; there would be a distributional effect, to be sure, but the net social loss would be $50,000. Where appropriate and accessible, this sort of accounting procedure can be applied in the property value loss calculations. The strip sampling method is, in fact, specifically designed to provide enough information to support its application. Note, as well, that the interior valuation process works from all directions for an island. The value of an interior plot of land can, as a result, rise, at least for a while. Proper sampling design for an island therefore involves looking at strips that run its entire length or width.

THE SOCIAL VALUE OF THREATENED COASTLINE

The final source of potential economic loss from sea level rise can be traced to the social value of the coastline that may be lost. Beaches are recreational areas, for example, which are generally available for use at the price of a beach badge; estimation of even their recreational value is therefore extremely difficult. The literature, building on work by Clawson (1966), suggests using transportation cost to construct at least a partial measure of value. More specifically, if using the beach is essentially free except for the cost of getting there and getting home, then the prices that families (e.g.) pay to use the beach are simply equal to the expenses that they incur simply getting to the beach and getting back home. Use surveys can then be employed to construct a demand curve for beach services by matching these prices with quantities demanded (people living various distances from the beach pay different prices to enjoy its services). The contribution of the beach to general social welfare can then be taken to be the usual consumer surplus area under this demand curve.

There are, of course, an array of other benefits generated by our coastlines which are not captured by this travel cost measure, and the problem of estimating the cost of losing a coastline region is one of measuring the value of all of these benefits. One approach that showed some promise in moving toward a more general measure was developed by Knetsch (1964) and David (1968). They both noted that property values increase with proximity to a recreation area like a beach. Since these increases reflect, quite simply, a willingness to pay for the general amenities provided by a beach, e.g., Knetsch and David argued that the sum of these increases could be employed as a measure of the value of that beach. As the beach disappears, then, the economic cost might be estimated by keeping track of the losses in proximity-generated surplus economic rents.

There are, however, several difficulties in applying the Knetsch-David notion directly. Some of the amenity, and thus some of the slope in a property value gradient, comes from views of the ocean that please residents with or without a beach. Attributing the entire slope to the beach proximity would therefore produce an overestimate of beach value. On the other hand, there are many people who do not live near the beach but

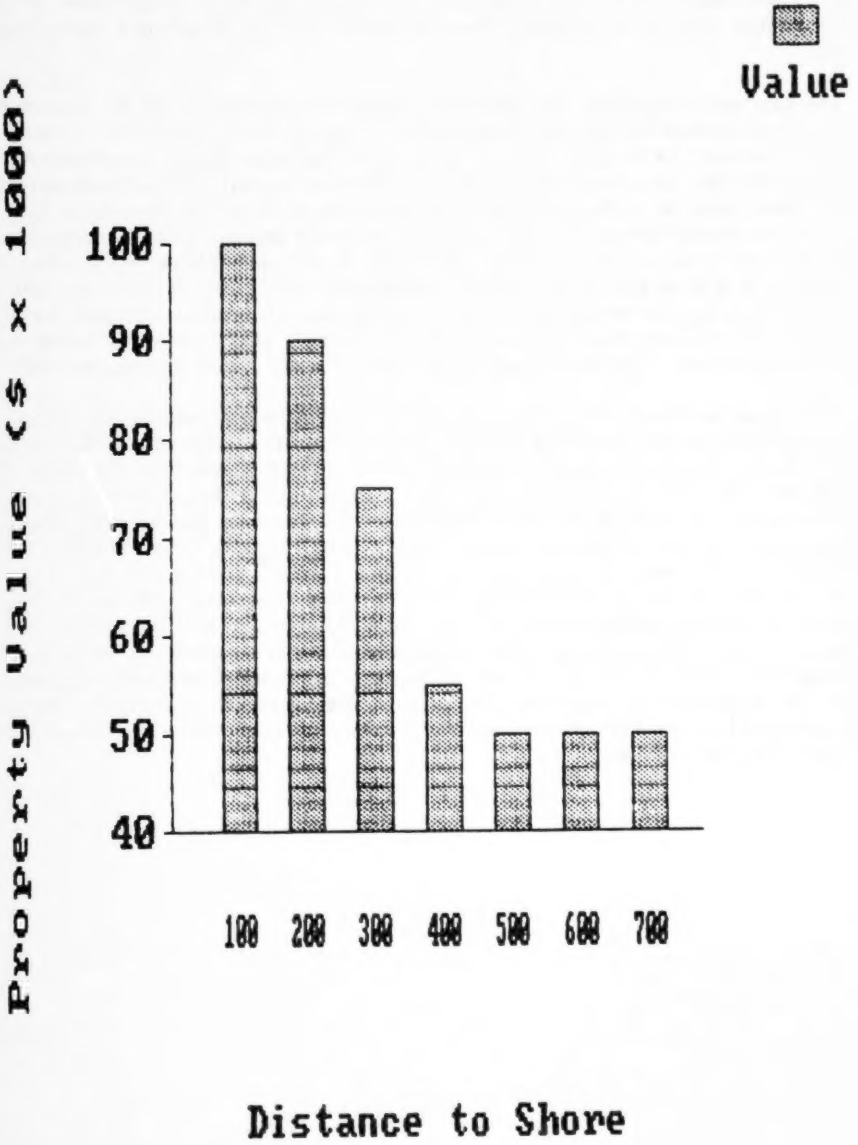

Figure 1. Distance to shore.

who nonetheless use the beach. Using a property value gradient exclusively would miss the value of the beach services that they enjoy, and would thus produce an under-estimate of beach value. Finally, there is considerable storm protection value provided to inland property by a beach and its associated dune structure which is captured by neither transportation cost surveys nor property value gradients. Still, a rough Knetsch-David style estimate can provide context -- an order of magnitude guess against which to judge more careful estimates derived in other ways.

The alternative procedure employed here attempts to account for all of the sources of value to the degree actually recognized by shoreline communities by judging beach value from community behavior when beaches are threatened. As a matter of law, in some places like Texas (Texas Open Beach Act), and of practice, in other places like New Jersey and North Carolina, a structure located along a beachfront must be abandoned and/or torn down when the land upon which it sits is inundated during the mean spring high tide. This allows the beach and presumably its dune to migrate inland, albeit at the expense of the property owner whose structure was in the way, but to the good of the inland community. By revealed preference, therefore, the social value of a beach must be at least as high as the value of beachfront structures which would be abandoned if the beach were to erode. It is, in other words, reasonable to assume that a beachfront structure is sacrificed to preserve the social value of coastline whenever a sea level rise scenario brings the water within a certain minimum distance of its foundation. Titus and Greene (this volume) submit that that minimum width is 40 feet.

Refer again to Figure 1 to see how this procedure might work operationally. Suppose, for the sake of argument, that $200,000 structures were located on each lot and that there were a 40-foot beach on the ocean side of the first lot. Recall that the lots are all 100 feet long moving away from the water. Now let the ocean rise, eroding 100 feet of beach and dune. What has been the cost? Any structure on the first lot is now within 40 feet of the ocean. To maintain the minimum beach width, therefore, that structure must be abandoned and perhaps torn down; the loss, attributable to the social value of the beach, is thus at least $200,000 derived from the lost structure. What about the property? An additional $25,000, representing half of the property value of an interior lot, has been lost, as well, because half of the first lot is gone.[4] Should this loss be added to the property loss accounting outlined in the previous subsection, or should it be attributed to the beach value accounting just noted? Ultimately, the answer to this question does not matter as long as it is not added in both places. Total vulnerability is, after all, the sum of the losses attributed to structure, coastline, and property. To emphasize the importance of preserving the social services provided by coastline, though, the accounting procedure adopted here attributes all property and structure loss associated with maintaining a coastline to the value of preserving that coastline.

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[4] Presumably the value of the next lot has increased according to the earlier story.

CHAPTER 2

VULNERABILITY FOR LONG BEACH ISLAND, NEW JERSEY

Estimates of economic vulnerability for Long Beach Island were prepared from a systematic sampling of assessed property and structure values along 25 separate strips of land. Two of the strips were designed to sample from atypical developments on the bay side of the northern part of the island. The remaining 23 were each approximately 200 feet wide, evenly distributed along the 18-mile length of the island and extending from the ocean to the bay; they were designed to sample from the more traditional development pattern of the majority of the island. Table 1 identifies the sample sites.

The general cross-sectional topography of the island, and thus of 23 of the 25 strips, is portrayed in Figure 2. There was some variation in development pattern. The north shows big houses on large lots and located well away from wide beaches; the south shows smaller houses on smaller lots packed up against narrower beaches. Nonetheless, their remarkable consistency made it possible to extrapolate inundation scenarios for each strip into integrated inundation scenarios for the entire island.

Beginning on the bay side, significant inundation will usually begin after a 1-foot rise; there are places where the bulkhead is a bit higher, but rarely could it restrain more than a 3-foot rise. Once begun, inundation will proceed quickly over the virtually flat area located between the bay and Long Beach Boulevard. On the ocean side of the Boulevard, the rate of inundation will slow as elevations rise more quickly, but it will by no means stop until the island is completely underwater. Ten feet above mean high tide is the usual maximum altitude of developed property at the base of the ocean-side protecting dunes.

Turning now to the ocean side, 100 feet of beach is lost on Long Beach Island for every 1 foot of sea level rise (Weggel et. al., this volume). Since the beach is less than 50 feet wide in some spots, particularly on the south end of the island with houses build up the inland sides to the tops of the dunes, maintaining the beach for social value will involve some economic loss even with a 6-inch rise. The cost accelerates until, at about 4 feet of sea level rise, nearly 75% of the $2 billion value of the island is lost.

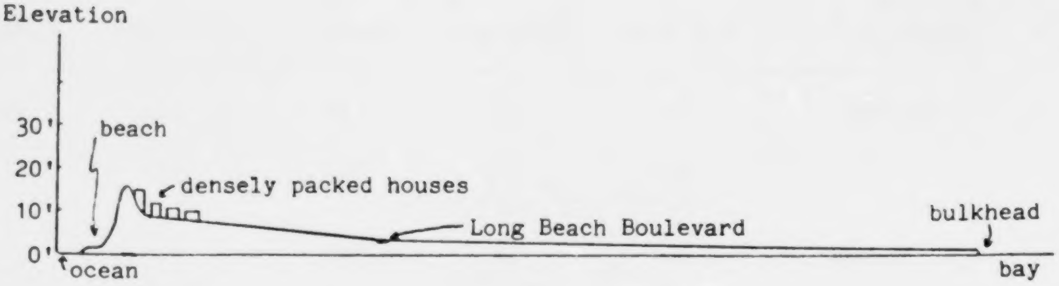
With inundation boundaries defined along each strip of the sample (and, by interpolation, along the entire length of the island) for 6-inch, 1-foot, 18-inch, 2-foot, 3-foot, 4-foot, and 6-foot sea level rise scenarios, it remained only to estimate the property, structure, and beach values threatened by each step of the process according to the procedure outlined in Chapter I. Estimates for both property and structure, normalized per eighth-acre lots, were produced directly from recent tax maps and a complete grand list for each level of inundation within each sampling strip. A comparison between asking price and assessed value for properties currently listed in the real estate market revealed a close match; no disparities of more than 10% were discovered, and no consistent bias in either direction was noted. Moving from these sampling estimates to property, structure, and beach value estimates for the entire island was finally accomplished by extrapolation, taking note of both the area inundated by each increment of sea level rise within the sample sites and the likely area inundated by each increment between sample strips.

Table 2 records the results of this entire process; it shows cumulative vulnerability estimates for the entire island for increment of sea level rise. Sampling errors (1 standard deviation) for the sample means are registered in the parentheses; the market works so well that thorough incorporation of the values recorded within the sample of 25 strips was sufficient to support t-statistics consistently well in excess of 20, in most cases, and never less than 10.

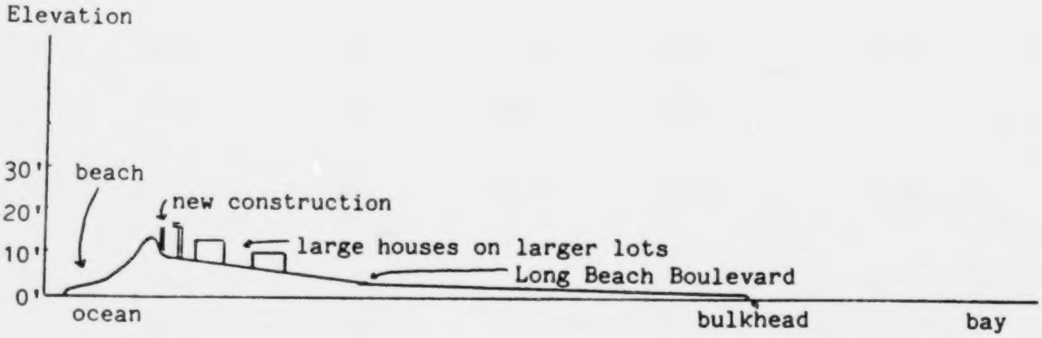
Notice that the total value attributed to the beach over the entire range of sea rise is $353 million. Comparing property values on Long Beach Island with the average of a small sample taken in Manahawkin (just across the bay), produced a rough Knetsch/David estimate of $346 million in total property value differential between the island and the mainland. There is, in addition, an estimated $89 million location premium for island

Table 1. Sample Sites -- Long Beach Island, New Jersey

Number	Tax ID	Southern Street	Northern Street
1	A-6	Cleveland Avenue	McKinley Avenue
2	A-33	Carolina Avenue	Inlet Avenue
3	A-52	Joshua Avenue	Magnolia Avenue
4	A-80	-----	Marshall Avenue
5	D-27	17th Street	18th Street
6	E-22	25th Street	26th Street
7	F-38	33rd Street	34th Street
8	H-11	Marine Lane	Ryerson Lane
9	J-22	Mississippi Avenue	Idaho Avenue
10	K-10	Kansas Avenue	Lillie Avenue
11	L-13	Cape Cod Lane	Ocean View Drive
12	M-24	Rhode Island Avenue	Massachusetts Avenue
13	0-11	Burwell Avenue	Dayton Avenue
14	0-32	Dupont Avenue	Goldsborough Avenue
15	0-62	Beardsley Avenue	Kirkland Avenue
16	0-98	46th Street	45th Street
17	0-128	37th Street	36th Street
18	R-20	-----	Windward Road
19	R-62	Roxie Avenue	-----
20	R-100	-----	Lagoon Road
21	T-7/8	87th Street	-----
22	T-40	-----	Loveladies Lane
23	T-144	-----	Beacon Drive
24	T-176	North-south through Loveladies	
25	W-5/6	Amherst Road	Arnold Boulevard


Elevation
30'
20'
10'
0'
beach
densely packed houses
Long Beach Boulevard
bulkhead
ocean
bay

South end of the island with a long stretch of land west of Long Beach Boulevard vulnerable to inundation from the bay and development packed up to land on top of the dune of a narrow beach.


Elevation
30'
20'
10'
0'
beach
new construction
large houses on larger lots
Long Beach Boulevard
ocean
bulkhead
bay

North end of the island with less property to the west of Long Beach Boulevard and larger houses on larger lots placed further from the dune and a wider beach. Some new construction is going in on the west side of the dunes.

Figure 2.

Table 2. Economic Vulnerability*

Sealevel Rise	Property	Structure	Beach	INCREMENT	TOTAL
0-6 inches	$0 (0)	$0 (0)	$15 (1)	$15 (1)	$15 (1)
6-12 inches	$0 (0)	$0 (0)	$40 (2)	$40 (2)	$55 (2)
12-18 inches	$80 (4)	$83 (4)	$62 (2)	$225 (6)	$270 (6)
18-24 inches	$70 (4)	$72 (4)	$50 (2)	$192 (6)	$462 (9)
2-3 feet	$129 (9)	$137 (8)	$115 (5)	$381 (13)	$843 (16)
3-4 feet	$315 (8)	$345 (7)	$45 (2)	$705 (11)	$1548 (19)
4-6 feet	$175 (4)	$184 (5)	$26 (1)	$385 (7)	$1932 (20)

---

* Measured in millions of dollars. The numbers in parentheses represent standard errors of estimation around the sample means of total or incremental dollar vulnerability. The total value of the island stands at approximately $2 billion.

property in direct proximity with the ocean and bay shorelines.[5] A total property value increment of $435 million can therefore be supported by a crude application of the Knetsch/David technique, suggesting that the structure/property based estimate of the social value of the beach reported in the tables is conservative.

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[5] This additional premium is computed by looking at the property value gradients along both the bay side and the ocean side of the island along its entire 18-mile length.

CHAPTER 3

DISCUSSION

Relating the vulnerability estimates of Table 2 to temporal, greenhouse induced sea level rise scenarios requires incorporating the natural 3.9 mm increase per year trend of the ocean off New Jersey. Table 3 tracks, in 10-year increments, sea level scenarios that attribute 50-cm, 100-cm, and 200-cm increases to greenhouse warming, respectively. Each includes nearly 1.5 feet in historical trend sea level rise between now and the year 2100. Table 4 translates the cumulative cost estimates of Table 2 into time-dependent estimates for each of the three scenarios; Figure 3 portrays each trajectory graphically. Annual loses are reflected in Figure 4 and Table 5. Both highlight the losses which can be expected on an annual basis for the decade following the indicated year. The figures show that marginal costs do not always climb; for the 2-meter scenario, e.g., marginal cost at 2100 is zero because the island was completely lost by the year 2090.

When real estate markets work well, market values reflect the discounted value of a stream of housing service income, implicit in the case of owner-occupied housing or explicit in the case of rental property. It is therefore interesting to consider the trajectory of lost economic rent that would have supported property values that were lost. Figure 5 illustrates lost economic rent embodied in cumulative economic cost for an assumed 10% return on investment. Higher returns would, of course, produce higher loss profiles; lower returns, lower profiles.

Table 3. Amount of Sea Level Rise for Various Scenarios

	Scenario*		
Year	50 cm.	100 cm.	200 cm.
2000	.14	.15	.18
2010	.31	.36	.47
2020	.51	.63	.87
2030	.73	.94	1.38
2040	.98	1.32	1.99
2050	1.25	1.74	2.71
2060	1.56	2.22	3.55
2070	1.89	2.76	4.49
2080	2.25	3.34	5.53
2090	2.63	3.99	6.69
2100	3.05	4.68	7.95

* Measured in feet, including the natural trend of 3.9mm per year. The scenario identification indicates the amount of sea level rise attributed to greenhouse warming above and beyond this natural trend.

Table 4. Cumulative Economic Vulnerability*

Year	50 CM.	100 CM.	200 CM.
2000	$3	$4	$6
2010	$9	$11	$14
2020	$15	$23	$39
2030	$34	$49	$215
2040	$56	$175	$457
2050	$155	$355	$671
2060	$280	$527	$1168
2070	$315	$720	$1633
2080	$405	$1041	$1831
2090	$518	$1540	++
2100	$873	$1651	++

* Measured in millions of dollars. The scenarios are identified in Table 3; the source of the cost estimates is Table 2.

++ The entire island is lost at this point.

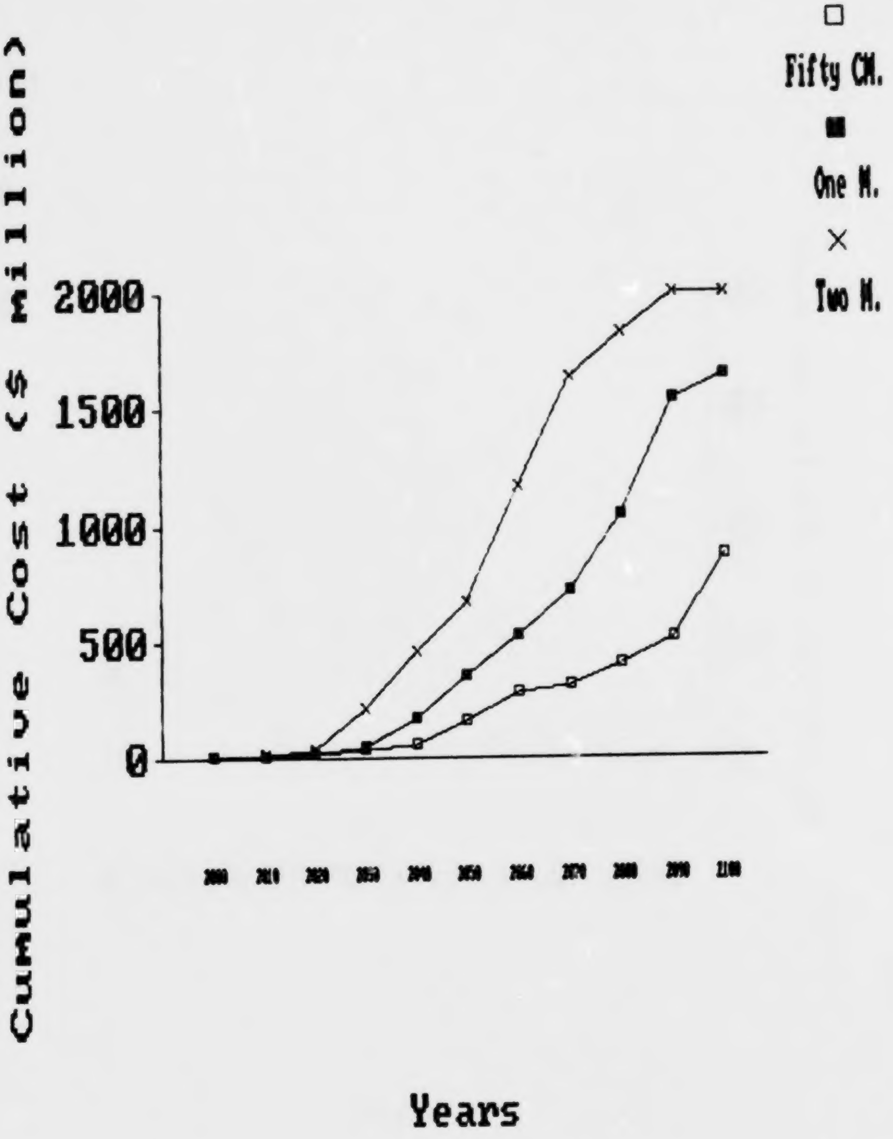
Cumulative Cost ($ million)
2000
1500
1000
500
0
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Years
□ Fifty CM.
■ One M.
× Two M.

Figure 3.

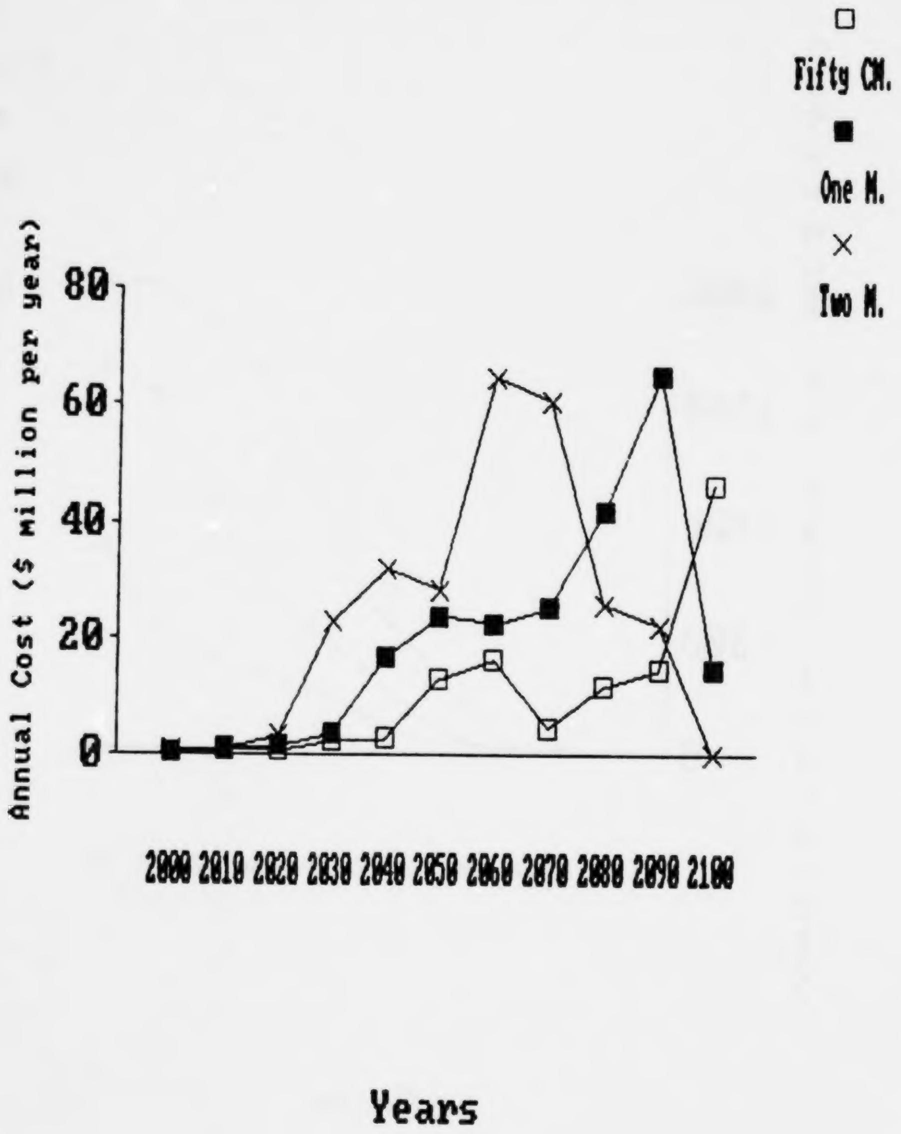
□
Fifty CM.
■
One M.
×
Two M.
Annual Cost ($ million per year)
80
60
40
20
0
2000 2010 2020 2030 2040 2050 2060 2070 2080 2090 2100
Years

Figure 4.

Table 5. Annual Increase in Economic Vulnerability*

Year	50 CM.	100 CM.	200 CM.
2000	$0.0	$0.0	$0.0
2010	$0.4	$0.5	$0.7
2020	$0.6	$1.0	$1.2
2030	$1.3	$1.8	$9.8
2040	$2.0	$7.8	$20.9
2050	$6.0	$14.3	$22.8
2060	$11.2	$16.6	$35.5
2070	$3.0	$18.3	$48.3
2080	$9.0	$25.7	$33.7
2090	$10.2	$41.0	$17.0
2100	$18.4	$30.5	++

* Measured in millions of dollars. The scenarios are identified in Table 3; the source of the cost estimates is Table 2.

++ The entire island was lost in 2090.

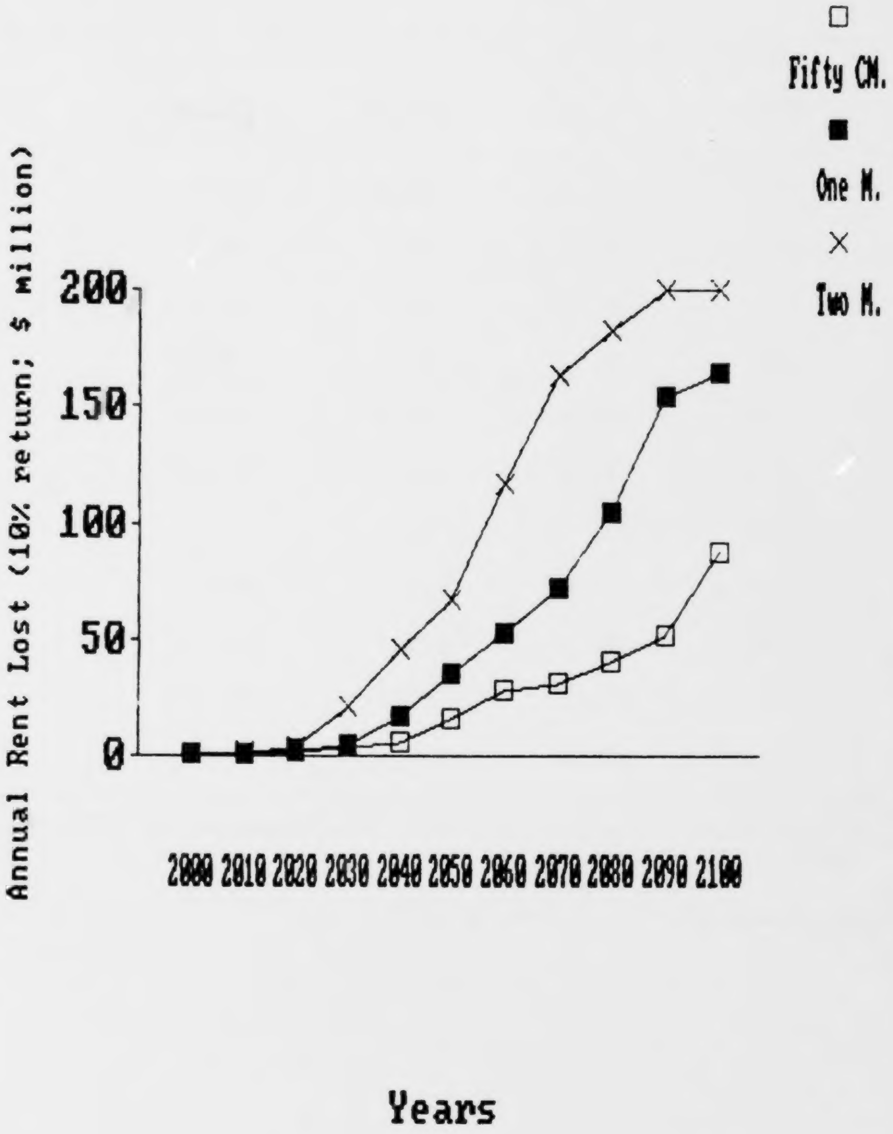
□
Fifty CM.
■
One M.
×
Two M.
Annual Rent Lost (10% return; $ million)
200
150
100
50
0
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Years

Figure 5.

CHAPTER 4

EXTENSIONS TO A NATIONAL STUDY

Straightforward application of the basic methodology recorded in Chapter 1 to a coastal sampling conducted by Park et al. (this volume) can be used to produce national and regional estimates of economic vulnerability. Park's study looked at the effects of 0.5-, 1-, and 2-meter sea level rise scenarios on 46 sites selected at regular intervals around the country. Together, these sites accounted for 10% of the U.S. coastal zone. Taking every other site to generate a first cut at an estimate of total vulnerability would therefore cover 5% of the coastal zone, and guarantee that particular regions would be included in the estimate roughly in proportion to their area. Basing a national estimate on this subsample would not support a precise result, but it would be sufficient to support an order of magnitude estimate of vulnerability. Going further may, in fact, give the spurious impression of increased precision given the uncertainties with which we view the distant future. More importantly, using the 5% subsample should certainly identify regions for which initial translations of vulnerability to cost would be most productive.

The precise details of applying the theory of Chapter 1 to the Park sample results need not be covered here, but at least one limitation should be mentioned. The Park surveys for each site usually record the effects of sea level rise for quadrants measuring 500 meters by 500 meters. Applying the notions of property value gradients outlined above to Park grids whose patterns frequently include quadrants extending 1000 feet inland is therefore troublesome, at best. It should, as a result, be expected that estimating vulnerability on the basis of average property values for each quadrant, taken from tax maps or housing and business census data, is the greatest precision which the inundation scenarios will support. How much accuracy is thereby lost? Initial comparisons of estimates derived from Park scenarios for Long Beach Island and the estimates reported in Chapters 2 and 3 above suggest that the answer to this question is "Not much." The law of large numbers seems to apply quite nicely, but any work toward a national estimate based on the Park surveys will include, as a quality check, a careful comparison with the more detailed work on Long Beach Island reported here.

CHAPTER 5

EXTENSIONS FROM VULNERABILITY TO COST

Frictional adjustment costs were first mentioned in Chapter 1, but they were dismissed there as being more closely related to costs than vulnerability. It is immediate, therefore, that modeling needs to be done to reflect their potential as the focus moves away from measuring the economic vulnerability to sea level rise and toward measuring the economic cost of sea level rise. Their very nature is, however, extremely suggestive. If the rate of greenhouse-induced sea level rise were known with certainty and there were enough time to respond, it is possible that the economic cost of sea level rise would be confined to adjustment costs and the value of the inundated land. Structure is mobile and would presumably be moved; coastal services can be provided by the new coastline. The question becomes, then, a matter of determining what happens when time is short and our foresight is imperfect and uncertain.

An initial line of analysis should look at the simpler component of this question. Some long-term growth modeling along a certain sea level rise trajectory should unravel the dependence of both relocation costs and the lost value of structure abandoned because time was too short on rates of economic growth, rates of economic depreciation, and rates of dislocation. It should include a thorough analytical structure which reflects how people and markets might reasonably respond to the effects of the trajectory, so it can reflect the time dependence of intertemporal costs. Only then can a decision whether or not to protect a particular piece of coastline be cast in a context that considers both the timing and the degree of protection.

A second line of analysis should then build on the first to incorporate uncertainty and risk. Critical here should be not only how people and markets respond to uncertainty over the long term, but also how people and markets learn what is going on. Figure 6 illustrates the current state of our knowledge about greenhouse-induced sea level rise, and the decisions we make now are dependent upon the relative likelihoods that we place on each possibility shown there. Our subjective distribution of possible futures will be different in the year 2000, and 2010, and so on; so we should expect that our decisions might change. Protection decisions, contingent upon certain events actually occurring, should, in fact, be considered explicitly -- perhaps as exogenous changes in economic environment made at certain times, but perhaps as endogenous variables in the modeling itself. In either case, it becomes important to explore the value of the information upon which decisionmakers weigh the costs of protecting a region against the costs of not protecting that region.

This second phase of the theoretical work will be difficult, so it should be conducted as one part of a two-part extension of the certainty modeling. With the results of the first cost analysis well established, it should also prove fruitful to apply the insights that it provides to specific regions taken from the vulnerability subsample. Looking at likely sources of costs for specific regions along the three scenarios will reveal which of the theoretical issues are more important than others and whether or not the ranking of their relative importance depends upon the region selected. Extension of the region-specific analysis to the more complex uncertainty modeling will then be able to focus on the most productive issues without wasting time on concerns that turn out, at least for one region, to be less significant.

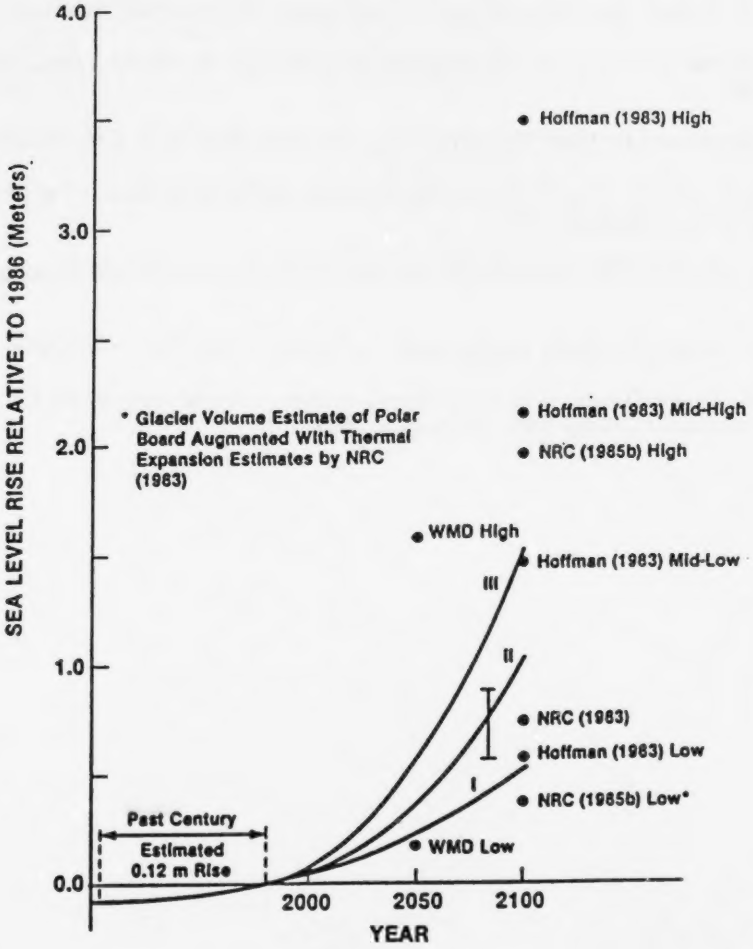

Figure 6. Estimates of future sea level rise (Hoffman, 1983, 1986; Meier, 1985; Revelle, 1983).

REFERENCES

David, E. L., "Lakeshore Property Values: A Guide to Public Investment in Recreation," Water Resources Research, (vol. 4, pp. 697-707), 1968.

Clawson, M. and J.L. Knetsch, Economics of Outdoor Recreation, Johns Hopkins, Baltimore, 1966.

Gibson, J., "Recreational Land Use", in The Valuation of Social Cost, (ed. David Pearce), George Allen & Unwin, Boston, 1978.

Hoffman, J.S., D. Keyes and J.G. Titus, "Projecting Future Sea Level Rise", U.S. EPA, Washington, 1983.

Hoffman, J.S., J. Wells and J.G. Titus, "Future Global Warming and Sea Level Rise" in Sigbjarnarson, G. (ed.) Iceland Coastal and River Symposium, 1986.

Knetsch, J. L., "The Influence of Reservoir Projects on Land Values," Journal of Farm Economics, (vol. 46, pp. 231-43), 1964.

Meier, M.F. et. al., Glaciers, Ice Sheets, and Sea Level, National Academy Press, Washington, 1985.

Revelle, R. "Probable Future Changes in Sea Level Resulting from Increased Atmospheric Carbon Dioxide," in Changing Climate, National Academy Press, Washington, 1983.

REFERENCES

David, E. L., "Lakeshore Property Values: A Guide to Public Investment in Recreation," Water Resources Research, (vol. 4, pp. 697-707), 1968.

Clawson, M. and J.L. Knetsch, Economics of Outdoor Recreation, Johns Hopkins, Baltimore, 1966.

Gibson, J., "Recreational Land Use", in The Valuation of Social Cost, (ed. David Pearce), George Allen & Unwin, Boston, 1978.

Hoffman, J.S., D. Keyes and J.G. Titus, "Projecting Future Sea Level Rise", U.S. EPA, Washington, 1983.

Hoffman, J.S., J. Wells and J.G. Titus, "Future Global Warming and Sea Level Rise" in Sigbjarnarson, G. (ed.) Iceland Coastal and River Symposium, 1986.

Knetsch, J. L., "The Influence of Reservoir Projects on Land Values," Journal of Farm Economics, (vol. 46, pp. 231-43), 1964.

Meier, M.F. et. al., Glaciers, Ice Sheets, and Sea Level, National Academy Press, Washington, 1985.

Revelle, R. "Probable Future Changes in Sea Level Resulting from Increased Atmospheric Carbon Dioxide," in Changing Climate, National Academy Press, Washington, 1983.

AN OVERVIEW OF THE NATIONWIDE IMPACTS OF SEA LEVEL RISE

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FINDINGS[1]

Global warming could cause sea level to rise 0.5 to 2.0 meters by 2100. Such a rise would inundate wetlands, erode beaches, exacerbate coastal flooding, and increase the salinity of estuaries and aquifers.

- A 1-meter rise by the year 2100 could drown approximately 25 to 80% of the U.S. coastal wetlands. Their ability to survive would depend largely on whether they could migrate inland or whether levees and bulkheads block their path of migration.
- A 1-meter rise could inundate 5,000-10,000 square miles of dryland if shores are not protected, and 4,000-9,000 square miles of dryland if only developed areas are protected.
- Most coastal barrier island communities would probably respond to sea level rise by raising land with sand pumped from offshore. Wide and heavily urbanized islands may use levees, while communities on lightly developed islands may adjust to a gradual landward migration of the islands.
- The long-term survival of coastal wetland ecosystems can be ensured if society takes measures to explicitly declare that developed low lands will be vacated as sea level rises. If implemented today, the purchase of future development rights required to follow such a strategy will be relatively inexpensive; if delayed, those same purchases will become too expensive, and forcing landowners to vacate their coastal property without just compensation would be considered an unconstitutional taking.

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[1] Although the information in this report has been funded wholly or partly by the U.S. Environmental Protection Agency, it does not necessarily reflect the Agency's views, and no official endorsement should be inferred from it.

CHAPTER 1

INTRODUCTION

In the last six years, coastal scientists, engineers, and policy makers have gradually begun to consider the prospect of a rise in sea level of one to ten feet over the next century. Because the interest of coastal zone managers in the practical consequences of sea level rise predated a widespread interest at the national level, most case studies on the effects of sea level rise have examined the implications for the specific decisions people make today, rather than estimating nationwide impacts. This paper summarizes the first nationwide assessment of the implications of future sea level rise.

CHAPTER 2

OBJECTIVES AND STRATEGY

Ideally, the goal of our research would be to know the economic and environmental impacts of all of the various scenarios of sea level rise for all possible policy response options and for every coastal community in the nation. Every community would then have sufficient information to rationally consider how they should respond. Moreover, we could estimate the nationwide impact by picking the best policy response option for each community and adding the costs. Because such a comprehensive analysis is not yet possible, this analysis had a more limited objective: a nationwide assessment that included as many factors as possible.

Our first step was to choose which of the impacts to study; we chose shoreline retreat for several reasons. First, we excluded saltwater intrusion because only one case study had been conducted; the processes are too complicated to meaningfully represent without detailed models; and the unavoidable economic and environmental impact of increased salinity appeared to be an order of magnitude less than shoreline retreat--and much more sensitive to drought than to sea level rise (Hull and Titus, 1986). We would have liked to have included flooding, which is closely related to shoreline retreat, but the cost of applying flood models to a large number of sites was prohibitive, and models of the resulting property damage are inaccurate without detailed surveys of the elevation and types of structures.

By contrast, examining the costs of (1) natural shoreline retreat and (2) holding back the sea seemed feasible. Estimating inundation of dryland simply requires that one know its elevation; wetland loss requires the elevation and an assumption regarding how rapidly the wetlands might accrete; a first-order estimate of beach erosion can be developed using topographic maps and a simple mathematical formula; and the value of lost property can be estimated using tax maps. The costs of holding back the sea are also fairly straightforward. The additional wetland loss is the area of developed property that would be protected (if these areas were not protected, wetlands would be created); the cost of nourishing beaches can be derived using data collected by the Corps of Engineers, and the cost of elevating land, houses, and infrastructure, and of erecting shore-protection structures, can be calculated by engineers based on experience.

Moreover, the procedures for assessing shoreline retreat tend to implicitly account for flooding caused by storm surges (at least after the first foot of sea level rise). Where development is protected from sea level rise, levees and pumping systems used for preventing inundation would also limit flooding; and raising barrier islands and the structures on them by the amount of sea level rise would leave flood risks constant.[2] Where development is unprotected, the estimates of lost land and structures probably account for the costs of increased flooding; although flood plains would move inland, the value of structures standing in the new flood plain would approximately be balanced by the inundated structures that are lost.[3] Nevertheless, for the first foot of sea level rise, examining shoreline retreat probably does not account for flooding: if development is protected, major coastal engineering measures probably would not be taken to counteract the first foot of rise, so the frequency of flooding would increase. If development is not protected, the first foot of rise would increase all flood surges but would not threaten many structures.[4]

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[2] This assumes that climate change has no impact on storm frequency of magnitude.

[3] This implicitly assumes that the development density of the coastal plain is uniform. Development in coastal areas tends to have the highest density in the first few rows of housing closest to the water (to obtain a waterfront view). The density of development in the rows just out of sight of the sea is slightly less.

[4] One foot is somewhat arbitrary; some areas might require levees with a smaller rise. However, we doubt that many areas will build levees or elevate land and structures until the sea rises at least one foot, but all coastal areas will experience incremental increases in flooding for any rise in sea level.

At the outset, it was clear that it would not be possible to estimate both the cost of shoreline retreat and the cost of holding back the sea in time to meet the report's congressional deadline. From previous studies and conversations with hundreds of state and local officials, it was clear that if we had to choose between the two, the cost of holding back the sea--at least in developed areas--was a more reasonable representation of the nationwide impact of sea level rise. We would learn little, for example, from estimating the value of buildings on Manhattan Island that would be lost if the sea was not held back; because of its value, the area would have to be protected. Furthermore, coastal scientists and engineers had been studying the physical implications of sea level rise, but few economists had investigated the economic implications.

By contrast, the wetlands study could examine the impacts of not holding back the sea as well. Estimating the net loss of wetlands requires one to consider (1) the conversion of existing wetlands to open water and (2) the conversion of dryland to wetlands. The former, which generally does not depend on coastal protection policies, is difficult because it depends on wave erosion and the ability of wetlands to accrete vertically; by contrast, the latter, which does depend on coastal protection, is fairly easy to estimate because over the course of a century virtually any sheltered area with an elevation between mean and spring hightide would convert to wetlands if not protected by levees and other structures.

Given the funding constraints and disciplinary boundaries for assessing sea level rise, we defined four studies:

(1) Park et al. would compile elevation data to estimate the inundation of dryland with and without the protection of developed areas and the loss of coastal wetlands for various shore-protection options.

(2) Leatherman would estimate the cost of dredging sand to nourish recreational beaches and, where necessary, to raise barrier islands in place, and develop data on the areas of developed barrier islands.

(3) Weggel et al. would estimate the cost of protecting developed areas along sheltered coasts, and would develop rough estimates of the cost of elevating houses and rebuilding infrastructure to accommodate a raising of Long Beach Island, New Jersey.

(4) Yohe would estimate the costs of losing land and structures, starting with Long Beach Island, New Jersey.

Besides providing an overview of the four papers, this paper undertakes a number of supplementary analyses. We examine statistical uncertainty due to sampling for the Park et al. and Weggel et al. studies. For the cost of protecting sheltered shorelines, we also combine the Park et al. estimates of inundated lowlands with the Weggel et al. cost assumptions for bulkheads and levees to develop cost estimates (1) for sea level rise scenarios that Weggel et al. did not consider and (2) that explicitly calculate the mix of levees and bulkheads necessary to protect each site. For the cost of protecting the open coast, we combine the cost factors of Weggel et al. and Leatherman's estimates of the area of U.S. barrier islands with Census data on housing densities to estimate the (non-sand) cost of raising barrier islands in place in response to a rise in sea level. We also use Leatherman's results to estimate national and state sand costs if unit sand costs increase as nearshore deposits are exhausted.

Figure 1 illustrates the relationships between the studies. The assessment of the nationwide costs of holding back the sea began with a case study of Long Beach Island, New Jersey. In the study of Long Beach Island, Leatherman and Park et al. followed the same procedures they would subsequently apply nationwide. Weggel et al. examined additional shore protection options as a check to ensure that the option used by Leatherman was reasonable.

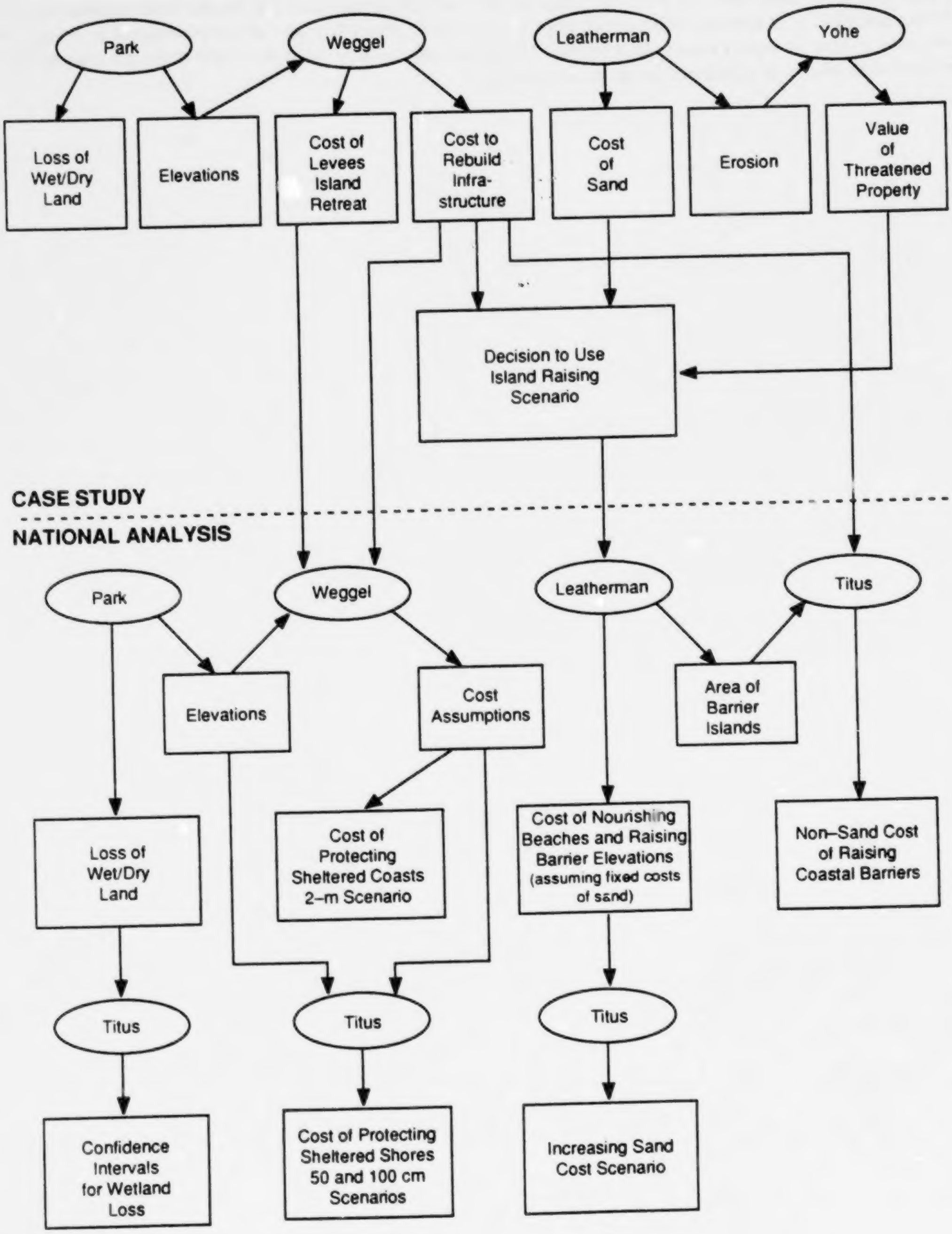
Park
Weggel
Leatherman
Yohe
Loss of Wet/Dry Land
Elevations
Cost of Levees Island Retreat
Cost to Rebuild Infra-structure
Cost of Sand
Erosion
Value of Threatened Property
Decision to Use Island Raising Scenario
CASE STUDY
NATIONAL ANALYSIS
Park
Weggel
Leatherman
Titus
Elevations
Cost Assumptions
Area of Barrier Islands
Loss of Wet/Dry Land
Cost of Protecting Sheltered Coasts 2-m Scenario
Cost of Nourishing Beaches and Raising Barrier Elevations (assuming fixed costs of sand)
Non-Sand Cost of Raising Coastal Barriers
Titus
Titus
Titus
Confidence Intervals for Wetland Loss
Cost of Protecting Sheltered Shores 50 and 100 cm Scenarios
Increasing Sand Cost Scenario

Figure 1. Overview of sea level rise studies -- authors and impacts.

The choice of shore protection options used in this study results from the need to develop a nationwide estimate of the costs associated with sea level rise; they are not necessarily presumed to be the most appropriate responses. The assumption of a uniform nationwide approach to shore protection was a computational necessity and not a reflection of how we expect society to respond. The justifications we provide show why these are reasonable options, but they should not be construed as an endorsement.

CHAPTER 3

SCENARIOS

We chose three scenarios of sea level rise for this study: 50, 100, and 200 centimeters (cm) by the year 2100. Following the convention of a recent National Research Council report (Dean et al., 1987), the rise was interpolated throughout the 21st century using a parabola, as shown in Figure 2. For each site, local subsidence was added to determine relative sea level rise. In addition to the three accelerated sea level rise scenarios, we also included a baseline scenario, which assumes that sea level will continue to rise at the historical rate of 12 cm per century or 14 cm by the year 2100.

We also devised three alternative scenarios of shoreline protection: no protection, standard protection, and total protection. In the no protection case, we assumed that no shoreline would be defended from a rising sea. For standard protection, we assumed that densely developed, sheltered coasts would be defended by either seawalls or levees (the cost of which was calculated without drainage systems for all but the Long Beach Island case study).[5] For the total protection case, every mile of sheltered coastal lowlands would be protected with either bulkheads or levees.

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[5] The exclusion of drainage system costs for the national assessment of protecting developed sheltered shorelines gives us a conservative (e.g., low) estimate of the costs that the country may face.

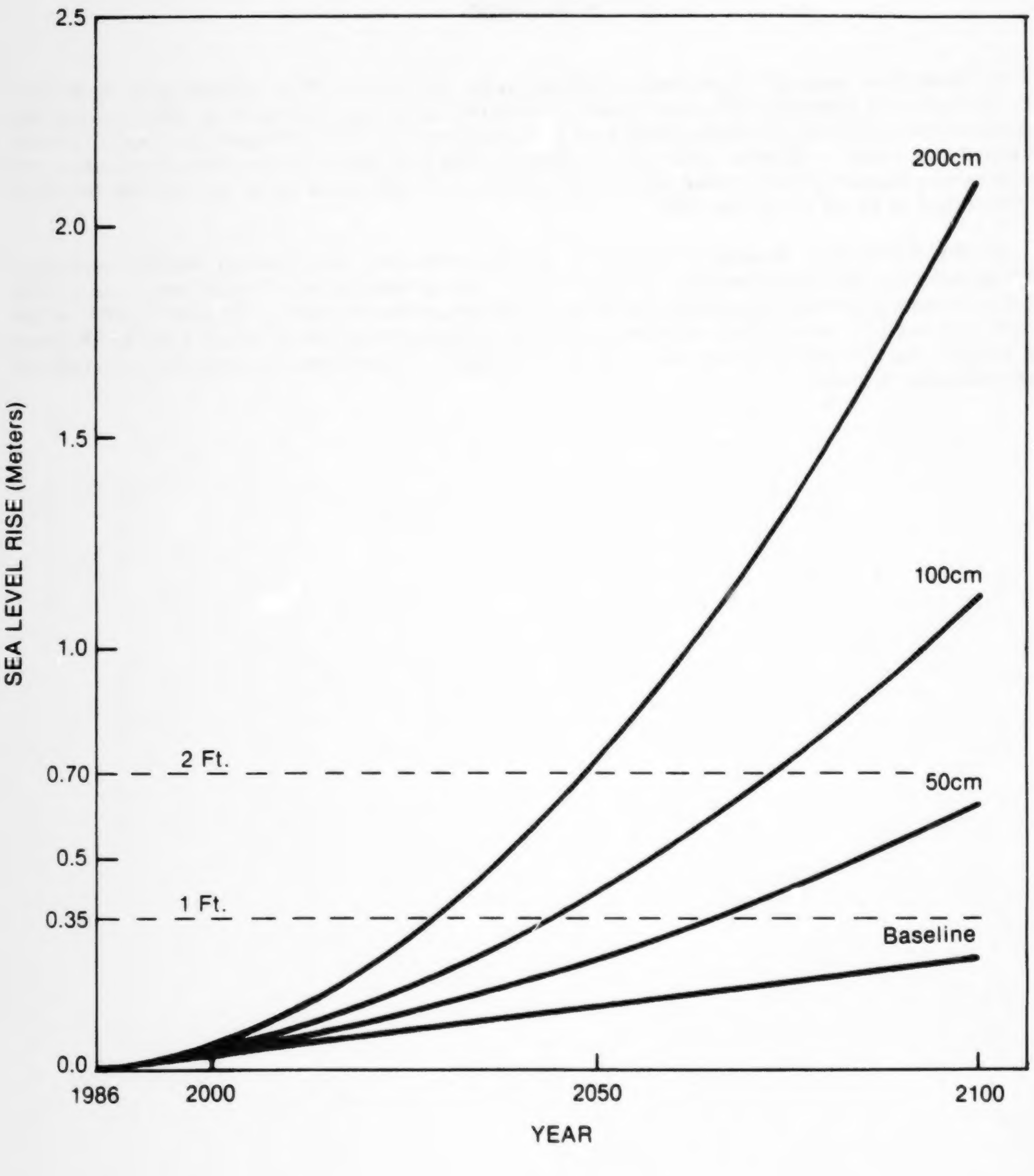

Figure 2. Sea level rise scenarios for Miami Beach (including local subsidence).

CHAPTER 4

CASE STUDY OF LONG BEACH ISLAND

We picked Long Beach Island (LBI), N.J., for the case study because we had experience there and because it provided most of the features that had to be considered: a narrow well-developed barrier island and a low-lying, partially developed mainland with extensive marshes.

Although the Park et al. and Leatherman studies of Long Beach Island were to be similar to their respective approaches in the nationwide assessment, we needed a more detailed engineering assessment from Weggel et al.: Leatherman was going to estimate only the cost of pumping sand onto beaches and coastal barriers; he was not going to estimate the cost of elevating buildings and roads. By examining Long Beach Island, Weggel et al. would provide us with engineering cost factors that we could apply to other communities. Moreover, we wanted to confirm the reasonableness of the hypothesis on which Leatherman's study would be based: that raising barrier islands was a reasonable assumption for estimating the cost of defending the open coast. Therefore, Weggel et al. also examined two alternative options: (1) a landward migration of the barrier island and (2) building a levee and drainage system. Finally, it would not have been feasible for Weggel et al. to visit every site the study would assess. Therefore, the investigators used Long Beach Island and five other sites to develop engineering rules-of-thumb that could be applied to a broader selection of sites.

METHODS USED IN THE LBI CASE STUDY

Loss of Coastal Wetlands

Park et al. sought to (1) compare the results of their model of wetland loss around Long Beach Island with the survey-based estimates from Kana et al. (1988), and (2) determine the impact of shore-protection efforts on wetland loss. First, the elevations of both wetlands and dryland had to be characterized. For wetlands, satellite imagery was used to determine plant species for 60- by 80-meter parcels. Using estimates from the literature on the frequency of flooding that various wetland plants can tolerate, it was then possible to estimate the percentage of time a particular parcel is underwater. Park et al. then used estimates of local tidal ranges to calculate the corresponding wetland elevation. For dryland, spot elevation measurements were used to interpolate between contours on USGS topographic maps and the elevations defined by the upper boundary of tidal wetland vegetation. To keep computations manageable, Park et al. aggregated the results into 500-meter cells; however, they also kept track of the percentages of the cell that corresponded to various elevations and wetland types.

Park et al. estimated the loss of wet and dryland for no protection and protection of developed areas. For the no-protection scenario, estimating the loss of dryland is straightforward. However, for calculating wetland loss, Park et al. had to consider the wetlands' vertical growth. For the baseline scenario, published rates of vertical accretion were used. For accelerated sea level rise, allowance was made for some acceleration of vertical accretion in areas with ample supplies of sediment, such as the tidal deltas.[6]

Sand Costs to Raise LBI and Maintain the Shoreline

Leatherman sought to estimate the cost of pumping enough sand to maintain the shoreline and gradually raise Long Beach Island. This required estimating the area of (1) the beach system, (2) the low bayside, and (3) the slightly elevated oceanside of the island. Leatherman used the "raising the profile" method, which we explain in a following section ("National Studies: Additional Methodological Considerations"). The area of the beach system was found by multiplying the length of the island times the length of the beach profile, which Leatherman calculated based on a 1-year storm, which in this case implied the 23-foot contour.[7] Topographic maps were used to estimate the area of land above and below 5 feet NGVD (1929),[8] which is about 4.5 feet above current sea level.

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[6] In some areas, vertical accretion is limited by sea level rise, not available sediment. If sea level rise accelerates some sediment flow that would otherwise wash onto beaches, sandbars, or into deep water, the sediment will instead wash into the wetlands.

Given the beach areas, the volume of sand was estimated by assuming that the beach system would be raised by the amount of sea level rise, and that the bay and ocean sides of the island would be raised after a rise in sea level of one and three feet, respectively. Leatherman assumed that sand would cost $7.85 per cubic yard, based on published sand inventories conducted by the Corps of Engineers.

Alternatives to Raising Barrier Islands

Examining the practicality of raising barrier islands required an assessment of two alternatives that had received more attention in previous studies: (1) protecting the island with seawalls and levees or (2) allowing it to migrate landward (imitating the natural barrier island overwash process by allowing the oceanside of the island to erode and pumping sand into the bayside to build land). After visiting Long Beach Island and the adjacent mainland, Weggel et al. designed and estimated the cost of an encirclement scheme consisting of dikes, levees, and a drainage system involving pumping and underground retention of stormwater. For island migration, the Bruun Rule (see Leatherman, this volume, for a description of this rule) was used to estimate oceanside erosion, and navigation charts were used to calculate the sand necessary to fill the bay landward by an amount equivalent to the oceanside erosion. For island raising and island migration, Weggel et al. used the literature to estimate the cost of elevating and moving houses and of rebuilding roads and utilities.[9]

In preparation for the national study, Weggel et al. estimated the cost of protecting the mainland shore in the vicinity of Long Beach Island and compared the detailed shoreline information with the rougher data provided by the 500-meter cells of Park et al.

Value of Threatened Structures

Yohe's case study is the only part of his report that was contracted to be available by publication of this report; the national estimate of the value of threatened structures and property is expected in the latter half of 1989. His objective was to provide economic information necessary to place the estimates of shore protection into their proper context (by estimating the value of land and structures that would be lost if the sea were not held back) after the other studies had been completed.

On the bay side of the island, the approach was relatively straightforward: any structures or land flooded at high tide would be considered lost. However, on the more elevated oceanside, Yohe had to specify the timing of the removal of the structures. Would they be removed only after the beach was lost and the structures were flooded at high tide or when the beach narrowed to a critical width? The latter approach was chosen for three reasons. First, the former approach would require Yohe to estimate the demand for beach area, something that was beyond the study's resources. Second, houses in front of the dunes would be vulnerable to storm damage and probably would not be able to stand in front of the dunes for more than a few years. Finally, in most cases, the value of the beach is greater than the value of the oceanfront structure, since the beach is one of the main reasons people buy property on or travel to barrier islands. Therefore, it seemed reasonable to assume that if a community decided to allow its shores to retreat, it would also require that structures be removed before they disrupted use of the beach. (The Texas Open Beaches Act already requires houses to be removed if they are within the dune vegetation area, and many other areas administratively follow this policy where possible.)

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[7] Large storms have an impact on sediment transport farther out to sea than do small storms. With larger storms come larger waves and excessively high and low tides. Thus, the larger the storm considered, the farther out to sea the beach profile extends.

[8] Because sea level has been rising, a contour that was five feet above sea level fifty years ago may only be 4.5 feet above sea level today. To avoid potential confusion, most maps today express elevations with respect to the "National Geodetic Vertical Datum" (NGVD) reference plane, which is a fixed reference unaffected by changes in sea level.

[9] Only the direct costs associated with raising the barrier island are included in the analysis. Indirect and less tangible costs that may be felt (i.e., the inconvenience suffered by the community when roads and utilities are dug up and raised, or when houses must be raised or moved as sand is pumped onto the island) are not included. These costs may be substantial and may change the outcome of our analysis. We are, however, unequipped to estimate them.

Nevertheless, some narrowing of the beach would probably be tolerated. Particularly along the northern part of the island, houses are generally set back over one hundred feet from spring high tide. To be conservative, Yohe settled on a minimum distance of forty feet from a structure to spring high tide, which is about equal to the distance from the crest of the dunes to the wet part of the beach. Because Yohe did not estimate the demand for beach area, he could not estimate the recreational benefits that would be lost if the beach narrowed. Nor did he consider the diminished flood protection value.

Given these behavioral assumptions, and estimates of erosion and inundation from Leatherman, Yohe determined which property would be lost from sea level rise for a sample of 25 strips spanning the island from ocean to bay. He then consulted tax maps to estimate the value of the land and structures that would be lost. Because a 50- by 100-foot oceanfront lot is typically worth about $100,000 more than an interior lot of similar size, Yohe had to consider the fact that this oceanfront premium would be transferred to another owner, not lost to the community. Thus, the value of land lost is the value of an interior lot.[10]

RESULTS AND IMPLICATIONS FOR THE NATIONAL STUDY

Table 1 summarizes the case study results for Long Beach Island for two policy options: (1) raising the island and bulkheading mainland sheltered shorelines and (2) natural shoreline retreat.

Wetlands Losses

The estimates by Park et al. largely confirmed previous estimates by Kana et al. (1988) that a 2-meter rise in sea level would drown 80% of the wetlands around Long Beach Island if shores were not protected. However, the results were not consistent with the hypothesis that wetlands loss would be substantially greater if the shores were protected; bulkheading the shores decreased the area of surviving wetlands by less than 10% in all scenarios. Two possible explanations are:

(1) A large portion of the wetlands are on marsh islands that would not be bulkheaded under any circumstances.

(2) At the coarse (500-meter) scale Park et al. used, the assumption of only protecting developed areas amounted to not protecting a number of mainland areas where the shoreline is developed but areas behind the shoreline are not.

As a result of the latter reason, it seemed reasonable to investigate the implications for coastal wetlands of protecting all coastal lowlands (total protection).

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[10] Adjustments were made to these data to ensure that the information was up-to-date. See Yohe's paper in this volume.

Table 1. Results For Long Beach Island Case Study

Wetland Losses[*]

(Percent of Original Area)

Response	50 cm	100 cm	200 cm
Raise Island/Bulkhead Mainland	45%	70%	78%
Natural Shoreline Retreat	50%	73%	80%

Response Costs[**]

(Millions of 1986 Dollars)

Response	50 cm	100 cm	200 cm
Raise Island/Bulkhead Mainland:			
Sand Cost	158	303	611
Elevating Houses/Roads	457	856	1,109
Total	615	1,156	1,720
Natural Shoreline Retreat:			
Loss of Rents	2,663	6,096	9,696

Sources:

Wetland Loss -- Park et al.
Sand Costs -- Leatherman
Other Engineering Costs for 2-meter scenario -- Weggel et al.
Lost Rents -- Yohe

NOTE: All researchers added approximately 20 cm of local subsidence to the global sea level rise scenarios. Therefore, our derivations of other engineering costs for 50- and 100-cm scenarios are based on Weggel et al. estimate of the cumulative cost in the 2-meter scenario when local sea level had risen 70 and 120 cm, respectively.

[*] Wetland loss estimates reflect Park's original run. His current paper reports on a subsequent run and results are substantially different.

[**] Dollar figures are cumulative, not discounted.

Is Raising Barrier Islands In Place a Reasonable Scenario?

The results by Weggel et al. clearly indicate that it would be much less expensive to raise Long Beach Island than to allow it to migrate landward, as shown in Table 2. A casual glance at the table also suggests that the option of building a levee around the island would be even less expensive. However, other considerations suggest that island raising would be more reasonable. First, a levee would eliminate the bayfront view. Second, because most of the levee costs would have to be borne all at once, financing it would be difficult. Third, Weggel et al. concluded that the levee would have to be built in the 2020's, and island raising could take place gradually between 2020 and 2100. This implies that the (discounted) present value of the levee cost would be greater.[11] For example, by the middle of the 2020's, the present value of the cost for island raising through the end of the century would be $400 million at a 3% discount rate and $200 million at a 10% discount rate, which would be far less than the $800 million for the levee system.[12] Fourth, a levee would alter the ecology of the undeveloped tracts of land. Finally, some people would feel unsafe residing on a barrier island below sea level.

Therefore, we concluded that it would be reasonable for Leatherman to assume that entire developed coastal barriers like Long Beach Island are raised in place, given that he could examine only one option for his national study. However, we caution that this assumption would probably not be reasonable for islands whose characteristics are vastly different. A very lightly developed island might find migration cheaper. For example, the analysis of Weggel et al. shows that landward migration is more expensive than island raising primarily because of the increased costs of rebuilding water and sewer lines and other utilities. But considerably less sand is required. (See Titus 1987b for a discussion of the institutional challenges this option would face.)

On the other hand, levees might be more practical for wide barrier islands where most people do not have a waterfront view. The most noteworthy example in the United States is Galveston, Texas, which is already protected by a seawall. Recently, people there have discussed totally encircling Galveston Island with a levee. The cost of raising an island with a given development density depends on the area of the island, while the cost of a levee depends on the island's perimeter. Thus, levees are least practical for narrow barrier islands. But for an island as long as Long Beach Island but five times as wide, the cost of a levee would be about the same, and the cost of raising the island would be five times as great.

A final question concerning the reasonableness of raising islands is whether the costs would be so great that it would be better to simply abandon the island. This is not likely to be a serious option for Long Beach Island in the next century, even for the 2-meter sea level rise scenario. Figure 3 compares the annual cost for elevating the island under the 2-meter scenario with Yohe's estimate of the value of the economic returns (rental income) lost in a particular year due to the cumulative loss of land and structures. The annual cost for elevating the island would gradually rise to $22 million/year by 2100. By contrast, the annual loss of rents (and property as well) would reach this level by the 2030's; by 2100, the annual loss of rents would be about $200 million, ten times the cost of shore protection. Right from the start, shore protection at Long Beach Island would be cost-effective and it would continue to be so. (The fact that shore protection is cost-effective means that the island has the resources to protect itself, but it does not address whether the residents, taxpayers, or contributors of greenhouse gases should bear the costs.)

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[11] In principle, some of the costs of a levee and drainage system could be deferred by raising the levee in stages, but the initial cost would be more than half of the total cost due to the need for land purchases, pumping systems, and design.

[12] The term "discounting" refers to a procedure by which economists equate dollars in one year with dollars in another year, generally by using a rate of return (interest rate). The present (discounted) value of one dollar Y years hence at a discount rate of R is:

$$1/(1+R/100)^Y.$$

Table 2. Results For Long Beach Island Case Study

Protection Costs for 2-Meter Sea Level Rise Scenario

(Millions of 1986 Dollars)

	Encir-clement	Island Raising	Island Migration
Sand Costs:*			
Beach	290	290	0
Land Creation/Maint.	0	270	321
Moving/Elevating Houses	0	37	74
Roads/Utilities	0	1,072	7,352
Levee and Drainage**	542	0	0
Total	832	1,669	7,747

Sources: Leatherman, Weggel et al.

NOTE: Weggel et al. estimated sand cost of $560 mil. ("Island Raising" above) differs from Leatherman's estimate of $611 mil. (Table 1 for 200 cm scenario) because each investigator made different assumptions regarding the closure depth of the beach profile (i.e. they assume different widths for the beach profile).

* Sand costs include the incremental periodic beach nourishment costs to raise entire beach profile.

** Designed to withstand 100-year storm.

CHAPTER 5

THE NATIONAL STUDIES: ADDITIONAL METHODOLOGICAL CONSIDERATIONS

SITE SELECTION

Ideally, we would have studied the entire coastal zone of the United States. Unfortunately, the cost of satellite data collection and interpretation made it impossible for Park et al. to encode more than 20% of the U.S. coast; because Weggel et al. used the same sites, they were similarly limited.

Site selection was motivated by two concerns: First, we wanted the sample to be unbiased and to yield statistically efficient estimates. Second, state and local coastal zone agencies expressed a need for information to be as site-specific as possible, and certainly aggregated at no more than the state level. Leatherman sought to satisfy both needs by examining every recreational beach in the country. To date, he has examined all of the beaches in all of the coastal states except Hawaii, Washington, Oregon, and Maine through New Jersey. In these states, which account for 20% of the nation's recreational open-coast beaches, he examined one beach per state.

For the other studies, however, we knew that sampling would be necessary. Thus we had to choose between a random sample and sampling at regular intervals. We decided to adopt the latter approach because it guarantees that particular regions will be represented in proportion to their total area in the coastal zone, while a random sample would have left open the possibility that Louisiana or another atypical region would have a disproportionate fraction of the sites. Such a condition would be more likely to significantly bias the nationwide estimates and might have left an important region uncovered. Accordingly, 92 sites were picked at regular intervals along the coast, accounting for 20% of the U.S. coastal zone. (This paper discusses only the results from a subsample of 46 sites for the Park et al. study, while the study of Weggel et al. includes the entire sample.) These studies did not consider Hawaii or Alaska.

In presenting results from the studies of Park et al. and Weggel et al., we group the sites into seven coastal regions, four of which are in the Southeast: New England, Mid-Atlantic, South Atlantic, South Florida/Gulf Coast Peninsula, Louisiana, Other Gulf (Texas, Mississippi, Alabama, Florida Panhandle), and Pacific Coast. Figure 4 illustrates these regions.

LOSS OF COASTAL WETLANDS AND DRYLANDS

Park et al. sought to test a number of hypotheses that previous publications had put forth:

(1) A rise in sea level greater than the rate of vertical wetland accretion would result in a net loss of coastal wetlands.

(2) The loss of wetlands would be greatest if all developed areas are protected (total protection), less if only densely developed areas are protected (standard protection), and least if shorelines retreat naturally (no protection).

(3) The loss of coastal wetlands would be greatest in the southeast, particularly Louisiana.

Park et al. applied the same procedures to the nationwide study that had been used in the case study. The only major difference was that for sites in the Southeast, where they considered the gradual replacement of salt marshes by mangrove swamps as areas became warmer.

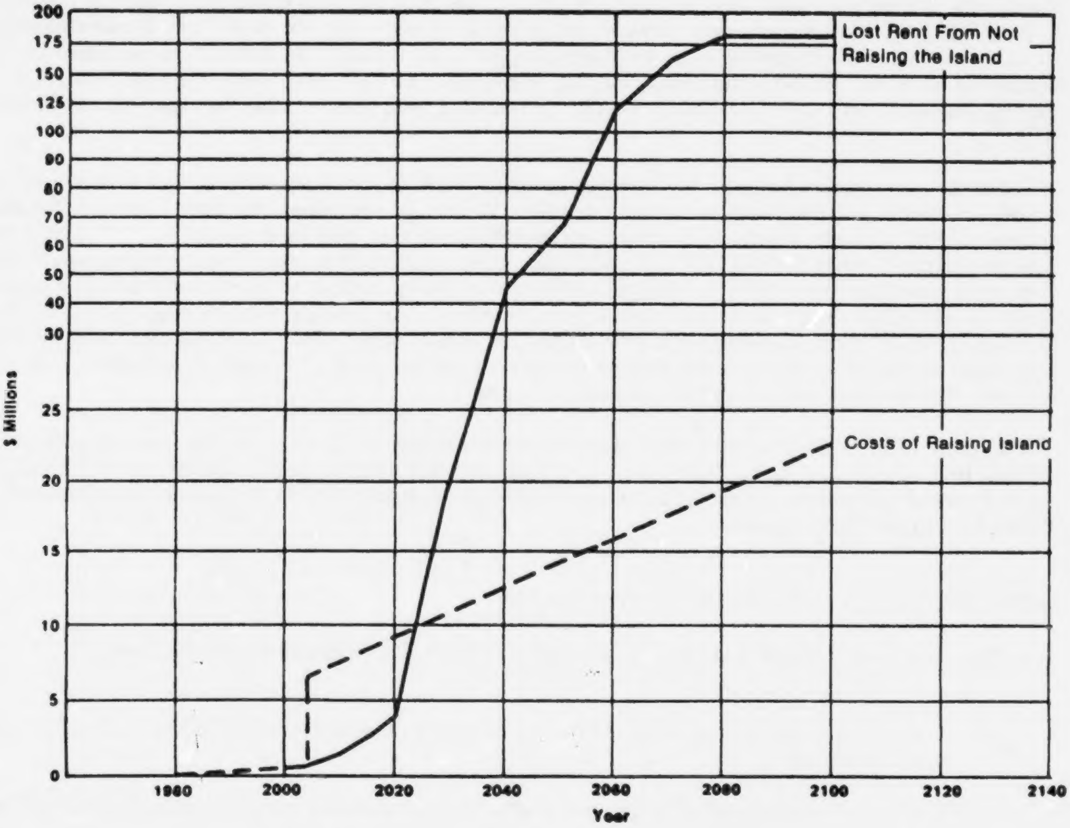

Figure 3. Annual cost of elevating Long Beach Island versus lost economic rent from not raising island.

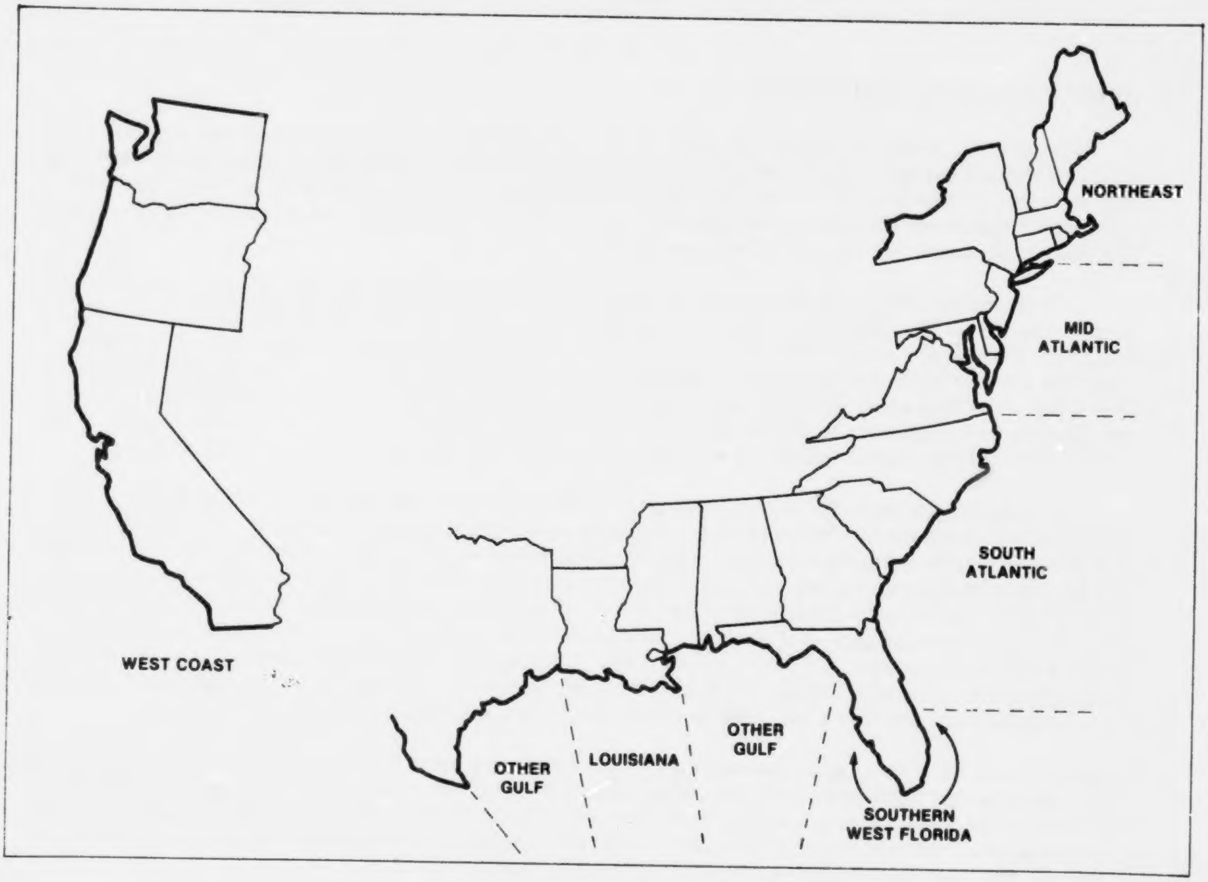
NORTHEAST
MID ATLANTIC
SOUTH ATLANTIC
WEST COAST
OTHER GULF
LOUISIANA
OTHER GULF
SOUTHERN WEST FLORIDA

Figure 4. Coastal regions used in this study.

The greatest uncertainty in the analysis of this study comes from the poor understanding of vertical accretion rates. This uncertainty could substantially affect the results for the baseline and 0.5-meter sea level rise scenarios. However, for a rise of one meter by 2100, there is no evidence that wetland accretion could keep pace with the 1- to 2-cm/yr accelerated rise that the scenario implies for the second half of the 21st century. For a 2-meter rise, the uncertainty regarding accretion rates has little, if any, practical significance; no natural amount of accretion would be able to keep up with sea level.

Another limitation is that Park et al. do not consider the potential implications of alternative ways of managing river flow. This is a particularly serious limitation for application to Louisiana, where a wide variety of measures have been proposed for increasing the amount of water and sediment delivered to the wetlands. Finally, the study makes no attempt to predict which undeveloped areas might be developed in the next century. If currently undeveloped areas are developed and protected, wetland losses will be higher.

DEFENDING SHELTERED SHORES

Weggel et al. sought to estimate the cost of protecting developed areas along sheltered waters. Their approach was to examine a number of index sites in depth to develop generalized cost estimates for protecting different types of shorelines; to use the topographic information collected by Park et al. for the sample sites to determine the area and shoreline length that had to be protected; to apply the cost estimation factors to each site; and to extrapolate the sample to the entire coast.

After assessing Long Beach Island, less detailed studies of protecting developed areas from a 2-meter rise were conducted at five other index sites: metropolitan New York; Dividing Creek, N.J.; Miami and Miami Beach; the area around Corpus Christi, Texas; and parts of San Francisco Bay. Weggel et al. then developed high- and low-cost estimates for the entire sample of sites, based primarily on shoreline lengths for the other sites provided by Park et al. The high estimates assumed that levees would have to be built; the low estimates assumed that only bulkheads would be necessary. The estimates netted out costs that would normally occur without sea level rise, such as rebuilding existing bulkheads as they reached the end of their useful lives.

The most serious limitation of this study is that cruder methods are used for the extrapolation than for the index sites. Even for the index sites, the cost estimates are based on the literature, not site-specific designs that take into consideration wave data for bulkheads or the potential savings from tolerating substandard roads. The exclusion of drainage systems in the nationwide costs understates the cost of protection since drainage systems will be necessary for areas protected by levees. The engineering assessment of Weggel et al. does not assess the environmental impacts of artificial drainage on water quality. Finally, the investigators were able to examine only one scenario: a 2-meter rise by 2100. Although the 1-meter rise is more likely, we chose to interpolate the impacts of a 1-meter rise from the 2-meter estimates of Weggel et al.; we felt this would yield more accurate estimates than if we chose to extrapolate from a 1-meter rise to a 2-meter rise.

Compared with the Leatherman and Park et al. studies, the methods of Weggel et al. are crude. This relative inaccuracy results more from the relative difficulty of achieving the Weggel et al. objective than from failure on the investigators' part to employ better methods. While literature, maps, and remote sensing provided Leatherman and Park et al. with sufficient data for all sites, a similarly valid sample for Weggel et al. would have required a few dozen prohibitively costly engineering assessments.

Nevertheless, the approach of Weggel et al. seems sufficient to provide a useful, conservative (that is, likely to understate the cost) first approximation. It is useful because it considers the length of shorelines that would have to be protected and uses typical cost-estimation factors for bulkheads and levees that should be accurate within a factor of two for a large sample. It is conservative because it does not include the cost of the extensive drainage systems that would accompany levees. In the Long Beach Island case, Weggel et al. estimate that the drainage system would be almost as expensive as the levees. Barrier islands have a large amount of shoreline for a small area; because drainage costs primarily depend on the area being drained rather than upon shoreline length, the costs for mainland areas could be several times the cost of building levees. Thus it is possible that the nationwide cost estimates of Weggel et al. are severalfold too low.

RAISING THE PROFILE: A SIMPLE PROCEDURE FOR ESTIMATING SAND REQUIREMENTS DUE TO SEA LEVEL RISE

Several studies on the impacts of sea level rise have estimated shoreline retreat, but only two studies of Ocean City, Maryland (Everts, 1985; Kriebel and Dean, 1985) have estimated the quantity of sand necessary to maintain the current shoreline, and the methods employed by those researchers require substantial amounts of data. However, a rough estimate can be developed simply by assuming that the entire beach profile is raised as much as the sea rises. For the this analysis, we define the variables as follows:

D = duration.

E = erosion.

H = vertical height of the beach profile from dune crest to closure depth (outer point of sediment transport).

L = horizontal length of the beach profile from dunes to point of closure.

P = average slope of the beach profile.

S = sand volume required to raise beach profile by amount of sea level rise.

SLR = sea level rise for a particular scenario by the year 2100 in feet.

The assumption of raising the beach profile by the amount of sea level rise is a corollary of the Bruun rule (1962),

$$E = SLR * L / H. \tag{1}$$

Erosion can be counteracted if $S = E*H$. Substituting $E = S/H$ into equation 1 and multiplying by H, we have,

$$E = SLR * L, \tag{2}$$

which is the same as raising the entire beach profile.

In the Ocean City report, Titus (1985) called this approach "Bruun" because the study was designed to compare estimates of shoreline retreat and sand requirements for different methods, and there was no point in changing names. However, in this report, we use the term "raising the profile method" because it more accurately conveys the procedure. Moreover, the fact that it is a corollary of the Bruun rule does not mean that all of the requirements for the Bruun rule must be satisfied for it to apply. Critics of the Bruun rule such as Devoy (1987) are concerned with the two-dimensional formulation's inability to predict the alongshore transport (e.g., from headland to embayment) that might be induced by sea level rise, as well as the fact that it ignores present day alongshore sand transport. However, when the objective is to estimate the sand requirements for an entire coast, the net alongshore transport is negligible.

Both methods share the requirement of defining the profile. Strictly speaking, we should not view the profile as f(x), but as f(x, D, epsilon), with D equal to the period of time the profile has had to adjust to sea level rise, with epsilon equal to the rate of sand transport viewed as sufficient for a location to be considered as being within the profile, and with x and f(x) equal to the horizontal and vertical dimensions, respectively. The domain of this function would extend farther inland and out to sea as D increases and as epsilon decreases (and hence the profile would be longer).

If epsilon is equal to the amount of transport necessary to bury one's feet in 60 seconds and D equals 10 minutes, the profile would be confined to the relatively small breakers and swash zone. If D is 12 hours with the same **epsilon**, the profile may extend over an extra 100 feet or so as tide goes in and out.

For a smaller **epsilon**, with D equal to a year, the profile might extend out to around the -20' contour along much of the Atlantic coast, and with a 50-year D, out to the -30' contour. Hallermeier (1981) outlines procedures for estimating the profile length for a particular D; topographic maps and navigation charts enable one to estimate height given the length. Thus, a time-dependent application of the Bruun rule would be,

$$(3)\qquad E(t) = \int_{-\infty}^{0} SLR'(t-D) * P'\delta D,$$

where SLR' equals the rate of sea level rise and P' is the derivative of the ratio L(D)/H(D). Similarly, a time-dependent means of raising the profile would be,

$$(4)\qquad S(t) = \int_{-\infty}^{0} SLR'(t-D) * L'(D)\delta D.$$

As a practical matter, the profile does not get much longer as D increases beyond 50 years, and most people are content to pick a single value for D and use Hallermeier's estimates; Leatherman's study also follows this convention. However, we hope that future studies will use more general formulations such as:

$$(5)\qquad E(t) = \sum_{D=0}^{T} [SLR'(t-D) * \{L(D)/H(D) - L(D-1)/H(D-1)\}]$$

where T ranges from 50 to 100 years, and

$$(6)\qquad S(t) = \sum_{D=0}^{T} [SLR'(t-D) * \{L(D) - L(D-1)\}].$$

The function L(D) could be approximated by fitting a polynomial through published estimates for specific values of D; H(D) could be approximated with whatever functional specification one uses to describe the shape of the beach profile.

We note that our formulation assumes that over a period of D years the profile adjusts to a D-year storm. This represents a maximum likelihood estimate, but not necessarily an unbiased or median estimate. For example, while we assume that the worst storm in a 100-year period will be the 100-year storm, the probability that the worst storm will be milder is $.99^{100} = 37\%$, while there is a 63% chance that it will be worse.

Given that Leatherman did not have time to employ the more general formula, he had to pick a value for D. Because the general approach was to underestimate the cost of sea level rise, Leatherman picked a 1-year storm.

COST OF PROTECTING THE OPEN COAST

Leatherman applied the "raising the profile" methods for all recreational beaches from Delaware Bay to the mouth of the Rio Grande plus California, which account for 80% of the nation's beaches. He also examined one representative site in each of the remaining states.

Leatherman's analysis provides a state-of-the-art assessment of the beach nourishment costs for the nation, with two caveats: (1) Although the sample of sites in the Northeast and Northwest are representative, complete coverage would have been more accurate; and (2) Leatherman used very conservative assumptions in estimating unit costs of sand. Generally, a fraction of the sand that is placed on a beach washes away because of insufficient grain size; and as the least expensive sand is used and dredges have to go farther offshore, sand costs will increase. For Florida, Leatherman used published estimates of the percentage of fine-grain sand, and assumed that the dredging cost would rise $1/cubic yard for every additional mile offshore the dredge had to go. For the other states, however, he assumed that the deposits mined would have no fine-grain sand and that dredging costs would not increase. Leatherman is also underestimating sand costs by assuming that the beach profile extends out only to the point where the annual severe storm would deposit sand.

A final limitation of the Leatherman study is that it represents the cost of applying a single technology throughout the ocean coasts of the United States. Undoubtedly, there are areas where communities would choose to erect levees and seawalls--particularly Galveston and other wide barrier islands in Texas--or to accept a natural shoreline retreat.

CHAPTER 6

RESULTS

RESULTS: NATIONWIDE LOSS OF WETLANDS AND DRYLANDS

Estimates of Park et al.

Table 3 compares the current area of wetlands estimated by Park et al. with the estimates from a recent NOAA inventory of coastal wetlands (Alexander et al., 1986). For the nation and for five of the seven regions, the differences between the estimates are within the sampling margin of error. However, the sample of Park et al. substantially underestimates the coastal wetlands of the middle Atlantic and the Pacific Coast, which together account for about 15% of U.S. coastal wetlands.

The Park et al. results generally supported the hypotheses suggested by previous studies (see Table 4). For a 1-meter rise in sea level, 66% of all coastal wetlands would be lost if all shorelines were protected, 49% would be lost if only currently developed areas were protected, and 46% would be lost if shorelines retreated naturally.[13]

As expected, the greatest losses would be in the Southeast. Figure 5 illustrates the loss of coastal wetlands for this region for three scenarios of shore protection. Even under the baseline scenario, a substantial fraction of Louisiana's wetlands would be lost. (See Chapter 6 of the main report to Congress.) Most other areas would experience slight gains in wetland areas. Of the 6046-8673 square miles of U.S. wetlands that would be lost from a 1-meter rise, 90-95% would be in the Southeast.

Analysis: Sampling Error

Table 4 illustrates wetland loss (in square miles and percentage terms) by region for each of the scenarios, along with sampling error (i.e., the standard deviation times the square root of the sample size). For the total protection scenario, the estimated loss of wetlands was greater than the sampling error for all regions, and hence could be viewed as statistically significant at the 60-70% level of confidence. However, to be significant at the 95% level, Student's-t distribution would require the losses to be 2.1-3.1 times as great as error (depending on sample size).[14] At this level of confidence, only the South Atlantic, Louisiana, and (barely) Mid-Atlantic show statistically significant losses for the total protection scenario; for other shore protection scenarios, only the South Atlantic and Louisiana are significant.

Given the small regional samples, the lack of statistical significance at the 95% level for area of wetlands lost could have been expected. However, we note that the uncertainty results largely from the fact that different sites had varying amounts of initial wetland coverage. We had hoped that this problem could be circumvented by considering percentage losses of coastal wetlands. Unfortunately, we found large standard deviations for percent losses as well, largely because most of the regions had at least one outlier (e.g., most of the sites in a region show 40-60% losses but one site shows a 1000% gain). We did not have time to undertake more

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[13] When all shorelines are protected, as sea level rises, the protective structures limit wetlands forming upland everywhere. On the other hand, with protection limited to developed shorelines, wetlands can form upland in undeveloped areas. Thus, the net area of wetlands is less after sea level rise under the total shore protection scenario than under the standard shoreline protection scenario.

[14] In the following analysis of wetlands and dryland losses, we have presented our results using 95% confidence intervals. We chose this level because we believe that even the losses at the low end of the interval are high enough to induce decision makers to plan ahead for sea level rise.

Table 3. Comparison of Park Baseline Data For Vegetated Wetlands (1985) and NOAA Wetlands Inventory

(Square Miles)

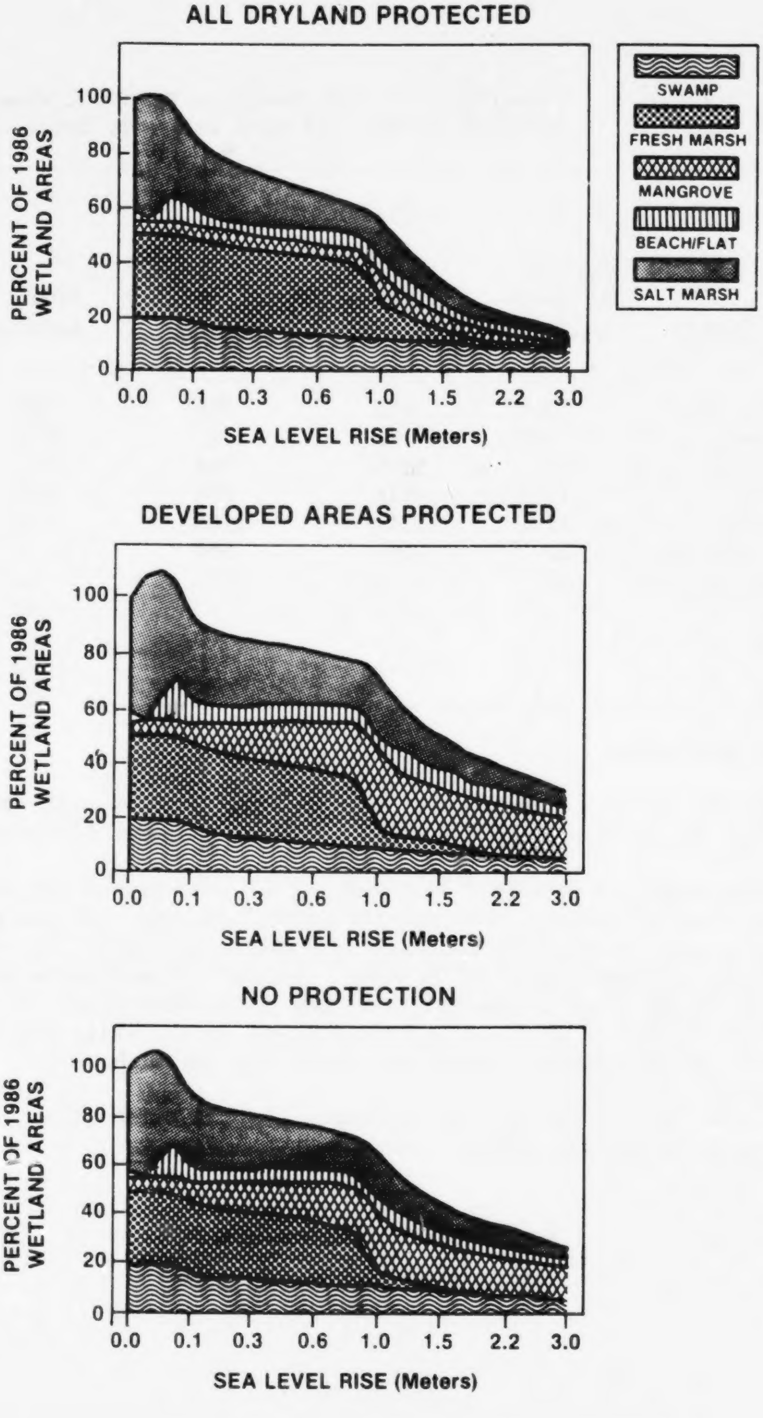
Region (Sample Sites)	Percent of Coast In Sample	Park Estimate	Sampling Error	NOAA Estimate*
Northeast (4)	3.4	600	389	382
Mid-Atlantic (7)	8.6	746	245	2080
South Atlantic (8)	10.1	3813	848	3967**
Louisiana (7)	13.7	4835	876	4491
Gulf Except LA (14)	12.2	3087	1169	3608
W/SW Florida (6)	10.7	1869	957	na
Other Gulf (8)	13.1	1218	673	na
West (6)	4.9	64	45	195
USA	9.7	13145	2105***	14723

na = not available.

* Alexander et al. (1986) also estimate the area of tidal flats for several states; we present only the sum of their estimates for vegetated wetlands.

** We have modified data from Alexander et al. to account for differences in the definition of coastal wetlands for North Carolina. Alexander et al. include all wetlands in coastal counties regardless of elevation, while Park et al. excluded wetlands above 12 ft NGVD. Because of extensive swamps above 12 ft in North Carolina's coastal counties Alexander et al. found the area of coastal swamps to be 8.4 times the area of marsh, while the boundaries of the sample of Park et al. found only 1.6 times as much.

*** Standard deviation of the estimate of the sum (i.e., sample standard deviation times the square root of the sample size).



ALL DRYLAND PROTECTED

DEVELOPED AREAS PROTECTED

NO PROTECTION

Figure 5. Southeastern wetland losses for three shoreline protection options.

Table 4. Regional and National Coastal Wetland Losses

Region	Standard Protection	Total Protection			Standard Protection			No Protection		
	Baseline	50 cm	100 cm	200 cm	50 cm	100 cm	200 cm	50 cm	100 cm	200 cm
Northeast										
Best estimate (sq mi)	39	88	93	100	55	58	33	27	8	-67
Best estimate (%)	7	15	16	17	9	10	6	5	1	-11
Sampling error (sq mi)	20	56	60	64	29	34	25	43	69	112
Mid-Atlantic										
Best estimate (sq mi)	-39	485	520	625	201	341	429	120	280	361
Best estimate (%)	-5	65	70	84	27	46	58	16	38	48
Sampling error (sq mi)	87	197	200	208	273	238	247	270	232	241
South Atlantic										
Best estimate (sq mi)	59	2295	2422	2542	1438	1669	1812	1313	1516	1606
Best estimate (%)	-2	60	64	67	38	44	48	34	40	42
Sampling error (sq mi)	201	526	506	510	516	558	621	517	573	656
South/Gulf Coast of Florida Peninsula										
Best estimate (sq mi)	-157	623	829	1020	92	157	165	63	122	120
Best estimate (%)	-8	33	44	55	5	8	9	3	7	6
Sampling error (sq mi)	110	274	380	477	230	313	474	235	320	481
Louisiana										
Best estimate (sq mi)	2271	2450	3742	4758	2368	3732	4686	2354	3732	4685
Best estimate (%)	52	56	85	99	54	85	99	54	85	99
Sampling error (sq mi)	421	338	735	882	385	735	902	385	735	902
Florida Panhandle, Alabama, Mississippi, Texas										
Best estimate (sq mi)	270	530	1031	1121	396	932	994	360	918	982
Best estimate (%)	22	44	85	92	33	77	82	30	75	81
Sampling error (sq mi)	209	279	761	812	306	779	821	319	779	823

Table 4. Regional and National Coastal Wetland Losses (continued)

West Coast										
Best estimate (sq mi)	-71	37	36	39	-286	-440	-651	-332	-518	-791
Best estimate (%)	-111	58	56	61	-447	-688	-1017	-519	-809	-1236
Sampling error (sq mi)	44	22	21	23	202	282	336	209	280	371
Southeast (original 11,735)										
Wetlands Lost:										
Best estimate (sq mi)	2,325	5899	8024	9443	4296	6491	7647	4090	6289	7342
Best estimate (%)	+20	50	68	80	37	55	65	35	54	63
95% low (sq mi)	a	4408(37)	5535(47)	a	2783(24)	3976(34)	4722(40)	2563(22)	3572(30)	4379(37)
95% high (sq mi)	a	7390(63)	10513(90)	a	5809(50)	9006(77)	10572(90)	5617(48)	8826(75)	10305(88)
Wetlands Left: [b]										
Best estimate (sq mi)	NC	NC	2843	2294	NC	NC	NC	NC	NC	NC
Best estimate (%)	NC	NC	24	20	NC	NC	NC	NC	NC	NC
95% low (sq mi)	NC	NC	779	848	NC	NC	NC	NC	NC	NC
95% high (sq mi)	NC	NC	4907	3740	NC	NC	NC	NC	NC	NC
United States (original 13,145)										
Wetlands Lost:										
Best estimate (sq mi)	2255	6511	8673	10206	4263	6441	7423	3904	6046	6892
Best estimate (%)	17	50	66	78	32	49	56	30	50	52
95% low (sq mi)	1168(9)	4944(38)	a	a	2591(20)	3813(29)	4350(33)	2216(17)	3388(26)	3758(29)
95% high (sq mi)	3341(25)	8077(61)	a	a	5934(45)	9068(69)	10495(80)	5592(43)	8703(66)	10025(76)
Wetlands Left: [b]										
Best estimate (sq mi)	NC	NC	4472	2897	NC	NC	NC	NC	NC	NC
Best estimate (%)	NC	NC	34	22	NC	NC	NC	NC	NC	NC
95% low (sq mi)	NC	NC	2302(18)	1302(10)	NC	NC	NC	NC	NC	NC
95% high (sq mi)	NC	NC	6642(51)	4492(34)	NC	NC	NC	NC	NC	NC

NC = Not calculated.

[a] = Confidence intervals not calculated for cases where sampling error exceeds best estimate.

[b] = Wetlands left only calculated for cases when sampling error exceeded best estimate for wetlands lost.

Table 5. Loss of Dryland

(Square Miles)

	Baseline	50 cm	100 cm	200 cm
Northeast				
No Protection	nc	139	235	472
Standard Protection	32	71	126	262
Mid Atlantic				
No Protection	nc	904	1205	1771
Standard Protection	448	705	928	1385
South Atlantic				
No Protection	nc	1094	1600	2561
Standard Protection	493	886	1272	2023
South Florida and Gulf Coast of Florida Peninsula				
No Protection	nc	768	1278	2035
Standard Protection	272	717	1196	1907
Louisiana				
No Protection	nc	1364	1417	1638
Standard Protection	1178	1249	1295	1449
Florida Panhandle, Alabama, Mississippi, and Texas				
No Protection	nc	905	1091	1548
Standard Protection	563	809	976	1405
Pacific Coast				
No Protection	nc	511	903	1771
Standard Protection	92	444	867	1537
United States				
No Protection				
Best Estimate	nc	5313	7727	11793
Error	nc	989	1289	1783
95% High	nc	7311	10330	15394
95% Low	nc	3315	5123	8191
Standard Protection				
Best Estimate	3078	4164	6661	9967
Error	804	982	1250	1747
95% High	4686	6147	9186	13496
95% Low	1470	2180	4136	6438

Table 5. Loss of Dryland (continued)

(Square Miles)

	Baseline	50 cm	100 cm	200 cm
Southeast				
No Protection				
Best Estimate	nc	4131	5386	7782
Error	nc	890	1084	1478
95% High	nc	5929	3196	4796
95% Low	nc	2333	7576	10767
Standard Protection				
Best Estimate	nc	3661	4739	7116
Error	nc	888	1075	1460
95% High	nc	5455	6910	10065
95% Low	nc	1867	2567	4166

nc = not calculated.

sophisticated approaches such as discarding outliers; hence we simply accepted the lack of significance at the regional level.

The one instance where we were able to reduce estimated sampling error concerns the "total protection" scenario. In a number of cases, we found that the standard deviation of remaining wetlands was much less than that for wetlands lost, as the table illustrates.

Despite the lack of significance for most regions, at the nationwide and southeast-wide levels of aggregation, the results are highly significant. The 95% confidence intervals for the nationwide percentage wetland loss are 38-61, 50-66, and 66-90% for the 50-, 100-, and 200-cm sea level rise scenarios and the total protection case and 17-43, 26-66, and 29-76% for the no-protection scenario. Statistical significance for the loss of dryland followed the same pattern. The best estimates indicate that if shorelines retreat naturally (no protection), a 1-meter rise would inundate 7727 square miles of dryland, an area the size of Massachusetts; with a 2-meter rise, 11,793 square miles could be lost. Again, most of the land loss would occur in the Southeast, particularly Florida, Louisiana, and North Carolina. The corresponding 95% confidence intervals are 3,000-8,000, 5,000-10,000, and 8,000-15,000 square miles lost for the 50-, 100-, and 200-cm sea level rise scenarios, respectively. Of course, with total protection of coastal lowlands, there would be no losses for any of the sea level rise scenarios.

RESULTS: THE NATIONWIDE COST OF PROTECTING SHELTERED SHORES

Estimates of Weggel et al.

Table 6 shows estimates from Weggel et al. for the index sites and the nationwide estimate. The index sites represent two distinct patterns. Because urban areas like New York would be entirely protected by levees, the cost of moving buildings and rebuilding roads and utilities would be relatively small.[15] On the other hand, Weggel et al. concluded that in more rural areas like Dividing Creek, N.J., only the pockets of development would be protected. The roads that connected them would have to be elevated or replaced with bridges, and the small number of isolated buildings would have to be moved.

Weggel et al. estimate that the nationwide cost of protecting developed shorelines from a 2-meter rise in sea level would be $25 billion if only bulkheads are necessary and $80 billion if levees are required. Unlike wetland loss, the cost of protecting developed areas from the sea would be concentrated more in the Northeast than the Southeast, because a much greater portion of the coast is developed in the Northeast. (The Southeast still accounts for a large percentage of total costs owing to its majority share of the U.S. sheltered shorelines.)

Analysis: Interpolating Results of Weggel et al. for 0.5- and 1-Meter Sea Level Rise Scenarios

Our objectives were to (1) interpolate the 2-meter sea level rise cost estimates developed by Weggel et al. to the 50 and 100-cm scenarios, (2) develop statistical confidence intervals of the costs of protection, and (3) explicitly consider whether particular sites would be protected with levees or bulkheads.

Weggel et al. assumed that even in the baseline scenario, bulkheads must be rebuilt every ten years. Their estimate for the cost of sea level rise is the cost of the additional height required by sea level rise. He assumes that in the baseline scenario, a five-foot bulkhead is necessary, at $130 or $500 per foot, and that costs rise with height to the 1.5 power. Thus, if SLR(t) represents the sea level rise in feet by the year t, the cost of bulkheads for the $130/foot estimate is simply,

$$\text{(7)} \qquad \text{Bulkhead Cost} = ((5 + \text{SLR})/5)^{1.5} * 130,$$

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[15] One reviewer noted that the cost of protecting Miami, Florida, may be too low. The city is located on a porous limestone base, a factor that may cause severe seepage and drainage problems.

Table 6. Cost of Protecting Sheltered Waters Against a 2-Meter Sea Level Rise

(Millions of 1986 Dollars)

Index Sites*	New Bulkhead	Raise Old Bulkhead	Move Building	Raise Roads & Utils.	Total
New York	57	205	0.5	9.5	272.3
Long Beach Island	3	4	2.7	3.8	13.7
Dividing Creek	4	6	4.8	18.2	33.0
Miami Area**	11	111	0.3	8.3	130.7
Corpus Christi	11	29	2.8	40.9	83.4
San Franciso Bay	3	19	2.0	20.0	44.0

Nationwide Estimate	Low	High
Northeast	6,932	23,607
Mid Atlantic	4,354	14,603
Southeast	9,249	29,883
West	4,097	12,802
USA	24,633	80,176

Source: Weggel et al.

* This is the cost for the low estimate only.

** Assumes no extraordinary seepage problems.

and the incremental cost due to sea level rise is,

(8) $$\text{Cost} = ((5 + \text{SLR})/5)^{1.5} * 130 - 130$$

We now present our procedure for the 1-meter scenario; the 50-cm scenario is analogous. The ratio of costs due to sea level rise incurred for a particular year between the 2-meter and 1-meter scenarios is,

(9) $$\text{RATIO}(t) = \text{COST\_1m}(t)/\text{COST\_2m}(t) = \frac{(5+\text{SLR\_1m}(t)/5)^{1.5} - 1}{(5+\text{SLR\_2m}(t)/5)^{1.5} - 1}$$

(Although the elasticity of total cost with respect to sea level rise is 1.5, the elasticity of costs due to sea level rise is only 1.08 over the 50- to 200-cm range.)

We are interested in estimating the cumulative cost for the 50- and 100-cm scenarios, which requires considering,

(10) $$\sum_{t=1986}^{2100} \text{COST\_1m}(t) \Big/ \sum_{t=1986}^{2100} \text{COST\_2m}(t)$$

Because Weggel et al. reported the denominator (i.e., the sum) and not the cost for specific years, we could not calculate this ratio precisely. Instead, we use a conservative approximation, COST_1m(2100)/ COST_2m(2100). (See Appendix 1 for proof that this ratio provides a conservative approximation.)

We wanted our analysis to explicitly consider the suggestion of Weggel et al. that $130/foot applies to areas above sea level that simply need bulkheads, while $500/foot applies to areas that would be inundated and hence need levees and pumping systems. Unfortunately, Weggel et al. were not able to determine the portion of developed shores that would require levees. However, Park et al. provide estimates of lost lowland. We assumed that the percentage of the developed shoreline requiring a levee would be equal to the percentage of coastal lowlands (below 12 feet NGVD) flooded by spring high tide under the no-protection scenario.[16]

Thus, we define the cost for protecting developed sheltered shorelines as,

(11) $$\text{Cost} = [500/130 * (\text{Lowland\_Lost}/\text{Lowlands\_1986}) + (1-\text{Lowland\_Lost}/\text{Lowlands\_1986})]$$
$$* \text{Weggel\_Cost\_130} * \text{Ratio}(\text{SLR})$$

where:

Weggel_Cost_130 = Weggel's estimate of the cost of protecting a site in the 2-meter scenario assuming $130/foot.

Lowlands_Lost = Area of lowlands lost at time t.

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[16] This assumption is conservative in that it underestimates the area of land that would need levees. Even today, cities like New Orleans that are completely protected by levees often have substantial areas above sea level, for two reasons: (1) even if only a small portion of the total land is low enough to need a levee, the entire shoreline can consist of lowland that needs protection, and (2) levees may be needed to protect areas from flooding during storms. The fraction of the shore requiring a levee would be less than the fraction of area below sea level only in unusual cases, such as a site with a straight lowland shore accompanied by uplands that jut into the sea like fingers.

Lowlands_1986 = Area of lowlands in 1986.

Ratio(SLR) = $((5 + \mathrm{SLR})/(5+6.56))^{1.5}$

SLR = Sea level rise for a particular scenario by year 2100 in feet.

6.56 = The rise in sea level by 2100 in feet for the 2-meter scenario.

Using this equation, we calculated the cost of protecting developed shores for each of the 46 sites in the Park et al. subsample.

As a final step, we sought to incorporate the additional information from the other 49 sites Weggel et al. examined. As Table 7 shows, the estimates from the full sample were within the sampling error for the Northeast, mid-Atlantic, and Southeast. However, by chance, the Park et al. subsample of the west coast had excluded all of the sites that would require significant amounts of bulkheads and levees; the full sample results in an estimate over six times as great. We followed the simple procedure of adjusting the estimates from equation 11 by the ratio of the Weggel et al. cost estimates for each of the four major areas of the nation; we adjusted statistical error by the ratio of errors for the two samples.

Table 7. Comparison of Weggel Low Cost Estimates For Park's Subsample and Full Sample

(Billions of 1986 Dollars)

	Subsample		Full Sample		Ratio*	
	estimate	error	estimate	error	estimate	error
Northeast	4.91	3.28	6.93	3.65	1.41	1.11
Mid-Atlantic	2.85	1.23	4.35	2.45	1.53	1.99
Southeast	11.22	3.43	9.25	2.12	0.82	0.62
West	0.65	0.02	4.10	0.37	6.31	23.40

* Ratio of Full Sample to Subsample.

Table 8 illustrates estimated costs of protecting sheltered shores for both the sample and subsample for each of the four major regions, and confidence intervals for the nation. For the three sea level rise scenarios, our estimated confidence intervals are 5-13, 11-33, and 29-100 billion dollars. Thus, for the nation at large, the elasticity of total cost with respect to sea level rise is 1.4; that is, a quadrupling of sea level rise from 50 to 200 cm increases costs sevenfold.[17] The elasticity would have been greater if the levee estimates had included the cost of drainage systems.

RESULTS: NATIONWIDE COST OF PROTECTING THE OPEN COAST

Leatherman Estimate of Sand Costs

Table 9 illustrates Leatherman's estimates. A total of 1920 miles of shorelines would be nourished. An area of 931 square miles would be raised, 235 of this after a 1-foot rise in sea level. As the table shows, two-thirds of the nationwide costs would be borne by four southeastern states: Texas, Louisiana, Florida, and South Carolina. Figure 6 illustrates the cumulative nationwide costs over time. For the 50 and 200 cm scenarios, the cumulative cost would be $2.3-4.4 billion through 2020, $11-20 billion through 2060, and $14-58 billion through 2100.

Analysis: An Increasing-Cost Scenario for Sand

In the past, we have shown that if unit sand costs increase substantially over time, a community that chooses to hold back the sea at first may eventually decide to migrate landward (Titus, 1987). However, that analysis was based on hypothetical increases in dredging costs. We wanted this study to provide at least a first-order estimate of how costs might escalate. In this section, we use the sand cost function Leatherman developed for Florida to develop an increasing-cost scenario. We emphasize that unlike our other estimates, no statistical interpretation can be attached to this estimate. We hope that this crude estimate encourages other researchers to consider cost-escalation in the future.

Leatherman's cost function for total available sand off Florida's Atlantic coast was based on the following:

Distance offshore (miles)	Available Sand (millions cu yd)	Unit Cost (dollars)
0-1	66	4
1-2	87	5
2-3	122	6
3-4	48	7
4-5	0	8
5+	Plenty	10

---

[17] Elasticities are used to measure the effect a change in one variable has upon another. In this case, the elasticity is calculated with the equation $\ln(C_1/C_2)/\ln(SLR_1/SLR_2)$, where "C" is cost and "SLR" is sea level rise.

Table 8. Cost of Protecting Developed Sheltered Shorelines Through 2100

(Billions of 1986 Dollars)

		Park Subsample			Weggel Full Sample*		
Region**	Base-line	50 cm	100 cm	200 cm	50 cm	100 cm	200 cm
Northeast (4/8)							
total	0.41	1.89	4.41	16.06	2.66	6.22	22.64
error	0.29	1.34	3.84	12.00	1.49	4.26	13.32
Mid Atl (7/15)							
total	0.31	1.33	3.35	9.13	2.03	5.12	13.97
error	0.11	0.54	1.45	4.31	1.07	2.88	8.58
S. Atl (8)							
total	0.58	2.86	7.75	21.64	nc	nc	nc
error	0.23	1.09	3.13	8.91	nc	nc	nc
S/W Fl. (6)							
total	0.15	0.65	1.64	4.44	nc	nc	nc
error	0.13	0.56	1.39	8.87	nc	nc	nc
Louisiana (7)							
total	0.11	0.37	0.65	2.12	nc	nc	nc
error	0.06	0.18	0.42	1.21	nc	nc	nc
Other Gulf (8)							
total	0.07	0.28	0.81	1.64	nc	nc	nc
error	0.03	0.11	0.24	0.65	nc	nc	nc
Southeast (29/54)							
total	0.91	4.16	10.82	29.84	3.43	8.91	24.59
error	0.27	1.24	3.46	12.65	0.77	2.14	7.82
95% low	nc	nc	nc	nc	1.87	4.59	8.79
95% high	nc	nc	nc	nc	4.99	13.23	40.39
Pacific (6/17)							
total	0.04	0.14	0.29	0.65	0.88	1.82	4.10
error	0.00	0.00	0.01	0.02	0.08	0.16	0.37
United States							
total	2.00	7.52	19.86	55.68	9.00	22.07	65.30
error	0.41	1.90	5.37	17.94	1.99	5.57	17.67
95% low	2.80	nc	nc	nc	4.98	10.82	29.60
95% high	1.20	nc	nc	nc	13.02	33.32	100.99

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* Full sample estimates are based on the ratios calculated in Table 7. Baseline was not calculated for the full sample.

** Numbers in parenthesis after each region are the number of sites in the subsample and full sample, respectively.

Table 9. Cumulative Cost of Placing Sand on U.S. Recreational Beaches, Coastal Barrier Islands, and Spits

(Millions of 1986 Dollars)*

	Baseline	50 cm	100 cm	200 cm
Maine**	23	119	217	412
NH**	8	39	73	142
Mass**	168	490	842	1546
RI**	16	92	161	298
CT**	102	516	944	1800
NY**	144	770	1374	2581
NJ**	158	902	1733	3493
Del	5	34	71	162
MD	6	35	83	213
VA	30	201	387	798
NC	137	656	1271	3240
SC	184	1158	2148	4348
GA	26	154	263	640
FL (AT)#	120	787	1938	8565
FL (G)	149	904	1688	4092
AL	11	59	105	260
MS	13	72	128	370
LA	1956	2623	3493	5232
TX	350	4188	8490	17608
CA	36	174	324	626
OR**	22	61	153	336
WA**	52	143	360	794
HA**	74	338	647	1268
Nation	3,790	14,515	26,893	58,824
SE	2,946	10,601	19,524	44,355

* Incremental cost due to relative sea level rise only.

** Indicates states where estimate was based on extrapolating a representative site to the entire state. All other states have 100% coverage.

# Florida Atlantic estimates account for the percentage of fine grain sediment, which generally washes away, and for cost escalation as least expensive sand deposits are exhausted. All other estimates conservatively ignore this issue.

Source: Baseline Costs derived from Leatherman.

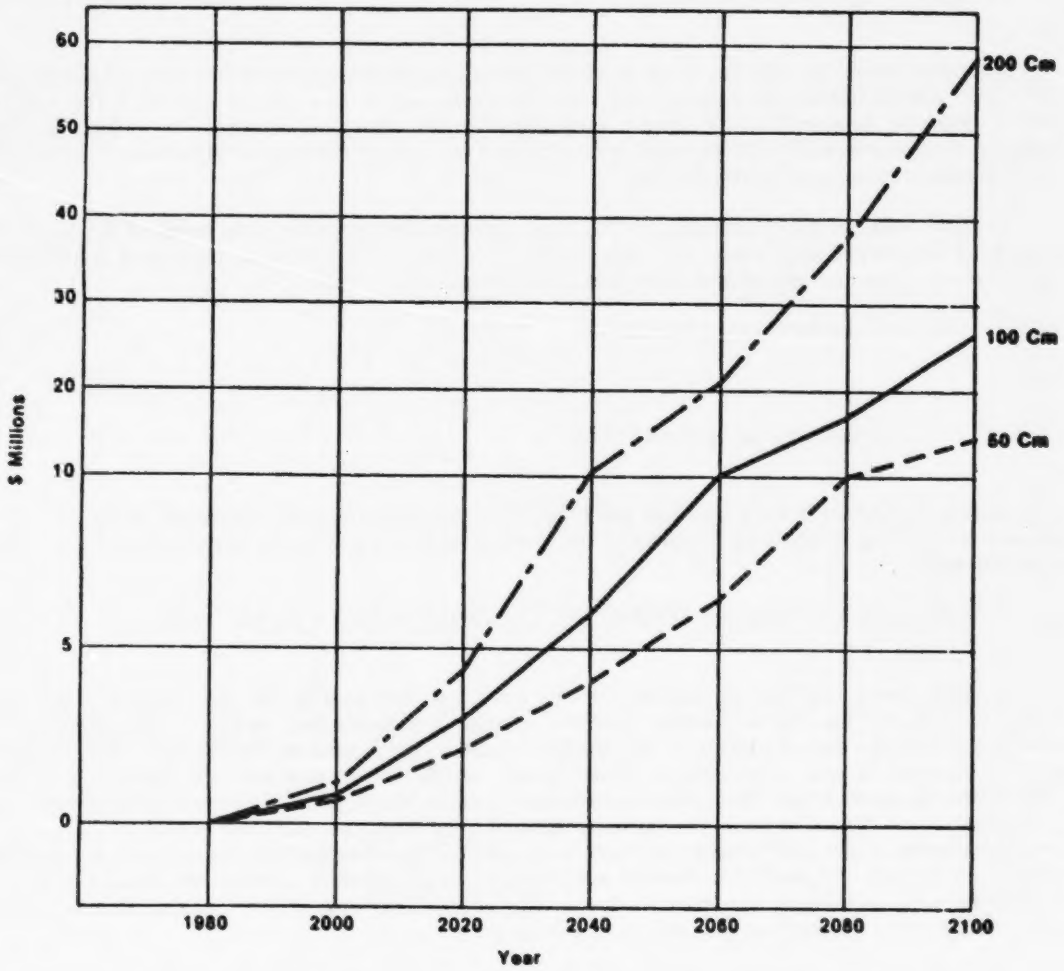

Figure 6. Nationwide cost of sand for protecting ocean cost.

The sand quantities are based on surveys by the Corps of Engineers. Unit cost estimates up to five miles assume that dredges pump the sand onto the shore, and use the generally accepted rule-of-thumb that each additional mile offshore adds \$1/cubic yard for the booster pumps that would be necessary. Leatherman assumed that for distances greater than five miles, pipelines would be infeasible, and barges and dump trucks would be employed at a cost of \$10/cubic yard, regardless of how far offshore one travels. Leatherman did not consider the possibility that improved technologies would reduce costs, nor the possibility that higher energy prices would increase costs.

Let C_{FL}(SAND) represent this cost function for Florida, and C_S(SAND) represent the function for a state S.

Ideally, we would like dC/dSAND to recognize the differences in sand availability, state-specific economic and environmental factors that influence the cost of dredging, and the fact that, all else equal, the amount of sand a particular distance from the shore is proportional to the amount of coastline. By scaling the Florida equation using state-specific data provided by Leatherman, we can accurately account for the latter factor and crudely attempt to account for the first two.

First, we scale the cost function C_{FL} by 293 miles, Leatherman's estimate of the length of the recreational beaches of Florida's Atlantic coast. This new function, which we call C^*, refers to the cost of nourishing one mile of beach. The unit cost of nourishing one mile of beach is $C^{*\prime}$. Then,

(12) $$C^*(\text{SAND}) = C_{FL}(\text{SAND}/293),$$

and

(13) $$C^{*\prime}(\text{SAND}) = C_{FL}'(\text{SAND}/293).$$

If we define C_S(SAND) as total sand cost and C'_S(SAND) as the unit cost for a particular state and a given amount of sand (e.g., $C'(0)$ is the current unit cost), we can scale for differences in current sand costs and shoreline lengths:

(14) $$C_S'(\text{SAND}) = C^{*\prime}(\text{SAND / SHORELINE\_LENGTH(STATE)}) + C_S'(0) - \$4.00.$$

This equation simply says that the unit cost of sand for a state increases by the same pattern as the cost in Florida, but (1) the base cost is whatever Leatherman found it to be for that particular state, and if a state's shoreline is L times that of Florida, it can dredge L times as much sand as Florida can before it must go another mile out to sea. Our additive incorporation of the current cost into this equation is probably conservative for states where the current cost is greater than in Florida, and too liberal in the minor case of Mississippi where the cost is less. Greater costs for sand often imply that one must already go farther out to sea than Florida, which may indicate that there is less sand at any distance from shore for such a state than there is for Florida. Although this situation would suggest a multiplicative relation, we decided to keep the additive formulation because cost diffences due to other factors such as wage rates, average deposit size, and using barges would not increase with the distance from shore.

Table 10 illustrates the shoreline lengths, base costs, and sand required for the three sea level rise scenarios for each state. Table 11 shows the implied sand requirements and cost per mile assuming constant costs. Table 12 shows the cumulative costs by state for the increasing cost scenario. Excluding Louisiana, the cost elasticity is 1.25 (i.e., costs rise with the 1.25 power of sea level rise).[18]

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[18] Louisiana was excluded from this calculation because even without sea level rise, the Louisiana coast will require large amounts of nourishment.

Table 10. Increasing Marginal Sand Cost Scenario For Dredging Sand

State	Developed Sandy Ocean Shoreline[*] (miles)	Unit Cost of sand ($\$/\text{yd}^3$)	Sand Required for Sea Level Rise Scenario (millions of cubic yards)		
			50 cm	100 cm	200 cm
Maine	31	4.00	30	54	103
NH	9	4.00	10	18	35
MASS	100	7.87	62	107	197
RI	27	6.00	15	27	50
CT	64	6.00	86	157	300
NY	120	7.85	98	175	329
NJ	125	7.85	115	221	445
DE	10	8.00	4	9	20
MD	9	6.00	6	14	35
VA	17	8.00	25	48	100
NC	143	7.00	94	182	463
SC	93	4.50	257	477	966
GA	16	4.00	38	74	160
FL(Atl)	293	4.00	177	340	1003
FL(Gulf)	251	4.00	226	422	1023
AL	36	4.00	15	26	65
MS[**]	43	2.75	26	47	134
LA[**]	85	5.00	525	698	1046
TX	230	9.25	453	917	1903
CA	78	4.00	44	81	156
OR	28	4.00	15	38	84
WA	48	4.00	36	90	199
HA	64	5.00	68	129	253

Source: Leatherman

[*] The calculations in this table are based on the assumption that National Parks and Wildlife Refuges would not be protected. Areas included under the Coastal Barrier Resources Act (COBRA) are not included unless connected to mainland by a bridge.

[**] None of the barrier islands in Mississippi and only one barrier island in Louisiana are developed. These calculations assume that all Louisiana barriers are raised for storm protection, and that the beaches and low resort communities behind Mississippi's barriers are raised.

Table 11. Average Quantity and Cost of Sand Per Mile of Shoreline*

	Sand per mile (millions of cubic yards)			Cost (millions of 1986 dollars)		
State	50 cm	100 cm	200 cm	50 cm	100 cm	200 cm
Maine	0.97	1.74	3.32	5.0	12.4	28.2
NH	1.11	2.00	3.89	6.1	15.0	33.9
MASS	0.62	1.07	1.97	5.4	9.9	22.3
RI	0.56	1.00	1.85	3.7	7.3	17.2
CT	1.34	2.45	4.69	11.1	24.4	51.3
NY	0.82	1.46	2.74	7.3	15.2	33.0
NJ	0.92	1.77	3.56	8.3	19.5	44.3
DE	0.40	0.90	2.00	3.4	8.3	23.0
MD	0.67	1.56	3.89	4.6	13.7	41.7
VA	1.47	2.82	5.88	16.0	34.5	77.3
NC	0.66	1.27	3.24	5.2	11.5	37.1
SC	2.76	5.13	10.39	24.0	48.9	104.1
GA	2.38	4.63	10.00	18.8	41.3	95.0
FL(Atl)	0.60	1.16	3.42	2.9	6.6	29.2
FL(Gulf)	0.90	1.68	4.08	4.7	11.8	35.8
AL	0.42	0.72	1.81	1.9	3.6	13.1
MS	0.60	1.09	3.12	2.1	4.6	22.3
LA	6.18	8.21	12.31	63.0	85.3	130.4
TX	1.97	3.99	8.27	25.1	55.9	121.1
CA	0.56	1.04	2.00	2.6	5.6	15.0
OR	0.54	1.36	3.00	2.5	8.6	25.0
WA	0.75	1.88	4.15	3.8	13.8	36.5
HA	1.06	2.02	3.95	6.8	17.2	38.5

* Scenario assumes that distribution of sand off Florida's Atlantic Coast is typical of sand distribution off all states' coasts.

Note: Cost escalation is based on the equation,
C*'(SAND) = A + \$4.00 for SAND = 0 to 225,000 cubic yards/mile A + \$5.00
for SAND = 225,000 to 522,000 cu yd/mi
A + \$6.00 for SAND = 522,000 to 938,000 cu yd/mi
A + \$7.00 for SAND = 938,000 to 1,100,000 cu yd/mi
A + \$10.00 for SAND > 1,100,000 cu yd/mi

for 0-1 miles off shore, 1-2, 2-3, and 5+ miles of shore, respectively (Leatherman's cost function shows no sand in the 4-5 mile range off Florida's coast, and our calculations for the other states follow this assumption, also). C*' is the unit cost of sand and A is the difference between the initial unit cost for a state and that of Florida (\$4.00).

Table 12. Cost by State of Protecting Open Coast Under Increasing Sand Cost Scenario*

(Millions of 1986 Dollars)

State	50 cm	100 cm	200 cm
Maine	155	384	874
NH	55	135	305
MASS	540	990	2,230
RI	100	197	464
CT	710	1,562	3,283
NY	876	1,824	3,960
NJ	1,038	2,438	5,538
DE	34	83	230
MD	41	123	375
VA	272	587	1,314
NC	744	1,645	5,305
SC	2,232	4,548	9,681
GA	301	661	1,520
FL(Atl)	850	1,934	8,556
FL(Gulf)	1,180	2,962	8,986
AL	68	130	472
MS	90	198	959
LA	5,355	7,251	11,084
TX	5,773	12,857	27,853
CA	203	437	1,170
OR	70	241	700
WA	182	662	1,752
HA	435	1,101	2,464
USA (Increasing Cost)	21,304	42,950	99,075
USA (Fixed Cost)**	14,515	26,893	58,824
Southeast (IC)	16,593	32,186	74,416
USA (IC - Excluding LA)	15,949	35,699	87,991

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* The calculations in this table are based on the assumption that National Parks and Wildlife Refuges would not be protected. Areas included under the Coastal Barrier Resources Act (COBRA) are not included unless connected to the mainland be a bridge.

** Leatherman national estimate minus the difference between Leatherman estimate for Florida (increasing cost) and the estimate implied by a constant cost of $4.00/cu yd.

Analysis: The Cost of Elevating Buildings and Roadways

If all the nation's developed barrier islands were developed like Long Beach Island, we could simply multiply the unit cost estimates described in the case study by the area of barrier islands that had to be raised. However, most islands are developed less densely. However, for barrier communities which are more densely developed, like Ocean City, Maryland, the infrastructure cost would not be proportionately greater. For the most part, a greater density reflects the presence of high-rises instead of single-family homes; the density of roads and utilities is not necessarily much greater. Thus, we use the following procedure:

(1) Collect census data for a random sample of coastal barrier communities on the number of buildings and divide by area to get density.

(2) Calculate the mean values and confidence intervals for densities in three coastal regions: the Gulf Coast, the Southeast Atlantic (Florida to North Carolina), and the mid and Northeast Atlantic States.

(3) Develop equations relating cost to shoreline length, area, and density, and apply the equation to the confidence interval for densities, for each of the three scenarios.

(4) Adjust the estimates (usually downward) for the 50- and 100-cm scenarios to account for the fact that the relative elevated ocean sides may not have to be raised for these scenarios.

Census Data

Table 13 illustrates census data on densities for the sites in our random sample. We note that there may be an upward bias, in that the Bureau of Census does not provide data if there are not at least 1000 year-round residents. On the other hand, there is a downward bias in that some of the barriers are lumped in with a township that extends to the mainland, which is generally less dense than the barrier. If census data were not available for a particular site, data from a nearby locale were used. In some instances, data from a nearby coastal (instead of a barrier) town had to be used. Another problem with census data is that it provides the number of housing units and the number of single-family homes, but not the total number of buildings, which we need to estimate road density. Thus, we were forced to use the number of single family homes as a proxy for building density. This last assumption effectively treats multi-unit structures as vacant lots; it is still more accurate than treating a condominium with 100 units as 100 houses.

Extrapolation Procedure

With means and confidence intervals for the densities calculated, we can now use the estimates of Weggel et al. to calculate the cost of elevating infrastructure for the nation's developed barrier islands. Because these costs are mostly related to roads, we begin with an equation relating Long Beach Island's development density (and, hence, infrastructure) to other barrier islands' level of development and size:

Table 13. Building Densities For a Sample of Coastal Barriers

				-(units/$mile^2$)-	
Site	Area ($mile^2$)	Housing Units	Single Units	Housing Density	Single Density
Gulf					
Galveston, TX	35.5	27,850	17,908	785	504
Freeport, TX	7.2	4,978	3,629	691	504
Grand I., LA	4.8	1,719	1,294	358	270
Gulf Shores, AL	8.8	1,567	1,327	178	151
Panama, FL	15.8	2,525	1,136	160	72
Belleair, FL	4.5	1,023	904	227	201
Siesta Key, FL	27.0	6,817	2,502	252	93
Manasota, FL	4.5	1,264	748	281	166
Ft. Myers, FL	2.6	5,685	2,376	2,187	914
Naples, FL	8.6	12,204	6,432	1,419	748
Marco I., FL	7.9	5,901	4,166	747	527

Mean Single Density: 377
Standard Deviation: 282
Standard Deviation of the Mean: 85

South Atlantic					
Key Biscayne, FL	1.3	4,635	1,928	3,433	1,428
Lauderdale-By-Sea, FL.	0.4	2,254	699	5,123	1,589
Palm Beach, FL	3.2	8,664	3,249	2,708	1,015
Vero Beach,FL	6.6	8,983	5,408	1,361	819
Cocoa Beach, FL	4.2	6,246	2,942	1,847	700
Daytona Beach, FL	3.0	1,267	212	422	71
Fernandina, FL	9.9	3,356	2,544	339	257
St. Simona, GA	7.4	3,400	2,591	459	350
Folly Beach, SC	1.9	1,128	774	594	407
Hilton Head, SC	43.2	9,768	7,922	226	183
Myrtle Beach, NC	16.8	10,107	5,508	602	328
Nags Head Area, NC	9.0	4,632	4,025	515	447
Wrightsville, NC	5.8	2,251	1,015	388	175
Long Bay, NC	5.3	2,967	2,314	560	437

Mean Single Density: 586
Standard Deviation: 469
Standard Deviation of the Mean: 130

Table 13. Building Densities for a Sample of Coastal Barriers (continued)

Site	Area (mile^2)	Housing Units	Single Units	-(units/mile^2)- Housing Density	Single Density
Mid-Atlantic/Northeast					
Va. Beach, VA	144.5	92,032	74,362	637	515
Ocean City, MD	4.5	18,221	3,116	4,049	692
Rehobeth, DE	1.9	3,111	1,593	1,637	838
Beach Haven, NJ	1.0	2,379	1,734	2,379	1,734
N. Beach Haven, NJ	1.7	5,326	3,920	3,133	2,306
Ship Bottom, NJ	0.6	1,781	1,322	2,968	2,203
Surf City, NJ	0.7	2,530	1,801	3,614	2,573
Sea Isle, NJ	2.3	4,595	2,762	1,998	1,201
Wildwood, NJ	4.3	16,664	8,267	3,875	1,922
Seaside Heights, NJ	0.4	2,728	1,004	6,820	2,510
Ocean Beach, NJ	0.8	4,022	3,877	5,028	4,846
Long Beach, NY	2.0	15,203	5,123	7,602	2,562
Atlantic Beach, NY	0.4	975	760	2,438	1,900
Narragansett, RI					
Pier	2.6	1,576	953	606	367
Town of	3.8	6,587	5,395	1,733	1,420
W. Yarmouth, MA	12.4	784	417	63	34

Mean Single Density: 1726
Standard Deviation: 1177
Standard Deviation of the Mean: 294

(15) $\text{Road\_Mileage} = \text{Length} + \text{LBI\_Secondary\_Road\_Density} * \text{Density} / \text{LBI\_Density} * \text{Area}$

where:

(16) $\text{LBI\_Secondary\_Road\_Density} = (\text{LBI\_Roads} - \text{LBI\_Length}) / \text{LBI\_Area},$

and Area and Length refer to the barrier island under analysis. Equation (15) says that if density is zero, the road mileage is equal to the length of the island in question. If the island is twice as long as LBI and has the same width and density, the road mileage is twice that of LBI. If the island has the same length but twice the area, the road length is not quite double that of LBI, since secondary roads are double but the primary road is the same length.

The secondary road density estimated by Weggel et al. is 14.3 miles per square mile. Weggel et al. also estimate the building density at 1949 per square mile; however, because only 73% are single-family houses, we adjust this downward to 1420, to be consistent with our approach of using census data for single family houses. Because the area of the island is 7.4 square miles, equation (15) becomes:

(17a) $\text{Road\_Mileage} = \text{Island\_Length} + 0.01007042 * \text{Density} * \text{Area},$

or,

(17b) $\text{Road\_Mileage} = \text{Island\_Length} + 0.01007042 * \text{Single\_Houses}.$

In the discussion of the case study, we noted that the cost for elevating houses and infrastructure worked out to $457, $856, and $1358 million for the 50-, 100-, and 200-cm scenarios, respectively. Because most of these costs apply to rebuilding infrastructure along roadways, we assume that the costs are proportional to road mileage. Given the island's 124 miles of roads, we multiply equation (17b) by the cost per mile of road for each of the scenarios, and we get:

(18a) $\text{Cost}(50\text{ cm}) = 3{,}685{,}000 * \text{Length} + 37{,}109 * \text{Buildings}$

(18b) $\text{Cost}(100\text{ cm}) = 6{,}903{,}000 * \text{Length} + 69{,}518 * \text{Buildings}$

(18c) $\text{Cost}(200\text{ cm}) = 10{,}952{,}000 * \text{Length} + 110{,}287 * \text{Buildings}.$

The intercept term, ranging from $3.7 to $11 million per mile, appears reasonable, when one considers that the roads are being replaced more than once in the high scenarios. However, the cost of $37-110 thousand per single house seems somewhat high at first glance. The cost results in part because Weggel et al. assume that communities would rebuild roads to normal engineering standards; however, this assumption is offset by the assumption that no other infrastructure would be necessary.

The cost does not seem quite so high if one remembers that the costs are incurred continuously over the course of a century; even in the high scenario, it is less than one thousand dollars per year per building. Moreover, the co-efficient also includes costs attributable to multi-unit housing and would be 25% less if we included all buildings.

Because we have sampled for density, we rewrite equation (18) as follows:

(19a) Cost(50 cm) = 3,685,000 * Length + 37,109 * Area * Density

(19b) Cost(100 cm) = 6,903,000 * Length + 69,518 * Area * Density

(19c) Cost(200 cm) = 10,952,000 * Length + 110,287 * Area * Density.

Although the 200-cm scenario involves raising the entire island, the 50- and 100-cm scenarios might only require that the low bay sides be raised. Therefore, we need to scale the equation to account for the part of the island that would be raised. We do this by multiplying the equations by the ratio bayside_area/area and dividing by the value of that ratio for Long Beach Island, 0.56. (Thus, for Long Beach Island, the equation is unchanged.)

(20a) Cost(50 cm) = 6,580,4000 * Length * Bayside_Area / Area + 65,947 * Bayside_Area * Density

(20b) Cost(100 cm) = 12,328,000 * Length * Bayside_Area / Area + 123,542 * Bayside_Area * Density

Because ocean as well as baysides would have to be raised in the 2-meter scenario, we do not bother to scale this equation, and simply use equation (19c).

We also use the unscaled equation (19b) as an alternative to equation (20b) for the 1-meter scenario, to account for the possibility that ocean sides of barrier islands might have to be raised even with a 1-meter rise. Leatherman assumed this to be the case, largely because for many islands, much of the land above 5 ft NGVD is within 2 feet of this contour. However, for Long Beach Island and other coastal barriers, most of the ocean side is above 8 ft NGVD. (Even land at the 10-ft contour might have to be raised with a 1-meter rise. Most of the islands with little land below 5 ft NGVD are along the Atlantic Coast. With a typical spring tidal range of 7 feet (and the fact that sea level is 6 inches above the NGVD reference elevation), land at the 10-foot contour is only 6 feet above spring ocean tide; with a 4-foot relative rise, it would only be 2 feet above the ocean's spring high tide. If the dunes were eroded by a prolonged northeaster, such low elevations of ocean side lots would greatly increase the risk of an inlet breach. If bay sides of barrier islands were already being raised, local officials recognizing that the sea would continue to rise after the year 2100 might conclude that raising ocean sides would be worthwhile as well.)

Results of Extrapolation

Table 14 illustrates our estimates of the non-sand costs of elevating barrier islands in place. For a 50 cm rise in sea level, Gulf coast barrier islands account for over 50% of the $11 billion cost, largely due to their lower elevations. By contrast, for a 2-meter rise, the Mid-Atlantic and Northeast would account for over 50% of the $96 billion cost because they are on average the most densely developed. Our estimates imply a cost elasticity of 1.6.

Table 14. Cost of Elevating Roads and Structures Assuming That Costs are Proportional to Building Density

	Gulf	South Atlantic	Mid Atlantic & Northeast	USA*
Shoreline Miles**	565	522	511	1,598
Bayside Area (mi^2)	181	24	30	235
Oceanside Area (mi^2)	325	167	204	696
Single Unit Building Density:				
Mean	377	586	1726	nc
Standard Dev	282	469	1177	nc
Total Cost (Billions of 1986 Dollars)				
50 cm	5.8	1.4	3.6	10.8
100 cm	10.9	2.6	7.2	20.7
100 cm (Alt Cost)	17.2	11.4	28.1	56.6
200 cm	27.2	18.1	50.1	95.4
Sampling Error				
50 cm	1.0	0.19	0.57	1.17
100 cm	1.9	0.37	1.09	2.22
100 cm (Alt Cost	3.0	1.63	4.75	5.85
200 cm	5.6	2.64	7.60	9.86

Cost(50 cm) = 6,580,400 * Length * Bayside_Area/Area + 65,947 * Bayside_Area * Density

Cost(100 cm) = 12,327,000 * Length * Bayside_Area/Area + 123,542 * Bayside_Area * Density

Alt Cost(100 cm) = 6,903,000 * Length + 69,518 * Area * Density

Cost(200 cm) = 10,952,000 * Length + 110,287 * Area * Density

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* Results are for the Atlantic and Gulf Coasts only; the Pacific Coast has no barrier islands. Sampling error is based solely on the variation of building density.

** Shoreline lengths are from Leatherman and refer to developed as well as developable sandy ocean shorelines.

CHAPTER 7

SUMMARY AND CONCLUSIONS

FINAL CAUTION

This paper has discussed the methods and results of four studies and our own analysis of the nationwide impact of a rise in sea level of 50-200 centimeters by the year 2100. The analysis was structured to enable consideration of three broad policy options: protect all shores, protect no shores, and protect only the areas that were developed by the middle of the 1980s.

It is the nature of first-cut national assessments to underestimate the cost of any undertaking, and this study is no exception. We have not identified every important cost; we have not estimated the magnitude of every cost we have identified; and we use assumptions that tend to understate the impact at each step of the calculations.

The estimates for barrier island raising are conservative because they assume (1) today's level of development and (2) do not consider the sand losses caused by major storms. The estimates for protecting sheltered shorelines are conservative because the complete cost of defending land from inundation would generally be greater than $500 per foot of shoreline; they only evaluate the cost of defending areas that are densely developed today; and our assumptions understate the portion of shorelines that would require levees.

We did not attempt to estimate the cost of protecting water supplies from saltwater intrusion or the cost of protecting lowlands from flooding. Nor did we examine the cost of saving Louisiana's coastal wetlands or of rebuilding municipal drainage systems.

Although the study provides nationwide estimates of wetland loss for three alternative policy options, it only provides a partial cost estimate for protecting currently developed areas. Future studies will have to assess the value of the (currently) undeveloped land that would be lost, as well as the economic losses that would occur from the loss of coastal wetlands.

Consideration of all three policy options should be conducted for specific areas; but nationwide cost estimates for the no-protection and total protection options would not be particularly meaningful. The no-protection costs would assume an eventual abandonment of the nation's beach resorts, as well as major portions of coastal cities such as Miami, Charleston, New York, and Boston--such an abandonment does not seem plausible given the relatively low cost of shore protection. The total-protection cost would assume a complete armoring of all U.S. tidal shorelines, which again does not seem reasonable.

SUMMARY RESULTS

Tables 15 and 16 summarize the nationwide and southeast-wide results of the papers comprising this volume. Fourteen thousand square miles of land could be lost to the sea from a 1-meter rise if shores are not protected, with dry and wet land each accounting for about half the loss. For approximately $100 billion, a thousand square miles of currently developed areas (accounting for about 7% of the threatened land) could be protected from inundation, but the loss of coastal wetlands would be greater.

Our estimates suggest that the cumulative cost of shore protection would be approximately $140,000 per acre. Thus, at the national level, protecting developed coastal areas appears to be cost-effective. Even if one merely compares this figure with the value of land and structures on barrier islands and coastal cities, these areas appear worth protecting. But this cumulative estimate implies that even at the end of the century, the annual cost of protection would be about $3,000 per acre--hardly a welcome prospect for coastal property owners but nevertheless, one well worth bearing in order to maintain the property.

Table 15. Summary of Nationwide Results

	50 cm	100 cm	200 cm
If No Shores Are Protected			
Land Lost			
Dryland Lost (sq mi)	3315-7311	5123-10330	8191-15394
Wetlands Lost (%)	17-43	26-66	29-76
Value of Lost Property ($bil)	Y	Y	Y
Cost of Coastal Defense ($bil)			
Open Coast	0	0	0
Sand	0	0	0
Elevate Structures	0	0	0
Sheltered Shores	0	0	0
If Developed Areas Are Protected			
Land Lost			
Dryland Lost (sq mi)	2200-6100	4100-9200	6400-13500
Wetlands Lost (%)	20-45	29-69	33-80
Value of Lost Property	Y	Y	Y
Cost of Coastal Defense	32-43	73-111	169-309
Open Coast			
Sand	15-20f	27-41f	58-100f
Elevate Structures	9-13	21-57f	75-115
Sheltered Shores	5-13	11-33	30-101
If All Shores Are Protected			
Land Lost			
Dryland Lost (sq mi)	0	0	0
Wetlands Lost (%)	38-61	50-82	66-90
Value of Lost Property	0	0	0
Cost of Coastal Defense	?	?	?
Open Coast			
Sand	15-20f	27-41f	58-100f
Elevate Structures	9-13	21-57f	75-115
Sheltered Shores	?	?	?

Note: All dollar figures are in billions.

Symbols:
Y signifies value that Yohe will calculate in future report.
? signifies value not currently being assessed.
f Interval represents estimates based on alternative formulae. All other intervals represent statistical uncertainty, except for totals, which contain both.

Table 16. Summary of Southeastern Results

	50 cm	100 cm	200 cm
If No Shores Are Protected			
Land Lost			
Dryland Lost (sq mi)	2300-5900	3200-7600	4800-10800
Wetlands Lost (%)	22-48	30-75	37-88
Value of Lost Property	Y	Y	Y
Cost of Coastal Defense			
Open Coast	0	0	0
Sand	0	0	0
Elevate Structures	0	0	0
Sheltered Shores	0	0	0
If Developed Areas Are Protected			
Land Lost			
Dryland Lost (sq mi)	1900-5500	2600-6900	4200-10100
Wetlands Lost (%)	24-50	34-77	40-90
Value of Lost Property	Y	Y	Y
Cost of Coastal Defense	19-28	42-75	127-174
Open Coast			
Sand	10-15f	19-30f	44-74f
Elevate Structures	5-9	10-40f	60-75
Sheltered Shores	2-5	5-13	9-41
If All Shores Are Protected			
Land Lost			
Dryland Lost (sq mi)	0	0	0
Wetlands Lost (%)	38-63	47-90	68-93
Value of Lost Property	0	0	0
Cost of Coastal Defense	?	?	?
Open Coast			
Sand	10-15f	19-30f	44-74f
Elevate Structures	5-9	10-40f	60-75
Sheltered Shores	?	?	?

Note: All dollar figures are in billions.

Symbols:
Y signifies value that Yohe will calculate in future report.
? signifies value not currently being assessed.
f Interval represents estimates based on alternative formulae. All other intervals represent statistical uncertainty, except for totals, which contain both.

But cost-effectiveness is not the sole criterion society should use to determine whether our shores should be protected from the effects of a rising sea; the value of resources like wetlands that might be lost if we protect our more tangible economic assets should be considered as well. Fortunately, it might be possible to protect both. The effort to protect coastal wetlands would be most successful if focused upon areas that are not yet densely developed. Abandoning developed areas would only increase the area of surviving wetlands by 5 to 10% --but at great cost. By contrast, limiting coastal protection to areas that are already developed (and allowing currently undeveloped areas to flood) would increase the area of surviving wetlands by 40 to 100%.

NEXT STEPS

Toward Better National Assessments

Although our nationwide estimates are based on samples of coastal sites, we have analyzed the implications of these results only at the national level, with the exception of the Long Beach Island case study. Although this is probably adequate for providing national policy makers with a sense of the magnitude of the threat from global warming and the need to develop anticipatory policies, it does little to suggest what those policies might be.

Once Yohe's assessment of coastal property values is complete, we will have a nationwide data base that will be adequate for conducting preliminary economic analyses of coastal policy options. For each sea level rise scenario, it will be possible to estimate whether and for how long particular coastal sites would be worth protecting (ignoring the value of wetlands, which market forces generally do). Such assessments will make it possible for national analyses to use a more realistic management scenario which assumes that all areas will be protected that are worth protecting; such a scenario will almost certainly fall between our total and standard protection scenarios.

Additional refinements in shore-protection cost estimates should focus on alternatives to raising barrier islands on the open coast and explicitly incorporating drainage costs in areas that would require levees. The former is necessary because island migration and levees may be more viable for some communities on the open coast; the latter is necessary because it is potentially as significant as construction of levees.

Estimates of the value of lost property will also have to be improved. Our proposed market-based shore-protection scenario will substantially understate the dryland protected and the wetlands lost as long as we assume today's level of development. Particularly in the Southeast, there is considerable low-lying forest and farm land that may be developed in the next thirty to one hundred years.

Toward Protecting Coastal Wetlands

Because a substantial acceleration in sea level rise is still decades in the future, we have argued that it is still too soon for society to implement most of the responses that sea level rise will eventually necessitate, but that one important exception is the protection of coastal wetlands (Titus, 1984; Titus, 1986; and Titus, 1988). Our hypothesis has been that coastal states outside Louisiana could maintain most wetland shorelines and minimize the loss of wetland acreage most efficiently by enacting a policy of "presumed mobility" that required that areas that are developed in the future (and perhaps a limited number of areas that are currently lightly developed) revert to nature 75-100 years hence if the sea rises enough to inundate them. There are many ways of implementing such a policy (e.g., restrictions on bulkhead reconstruction, state regulations, long-term leases, conditional land ownership), but the success of this option requires that it be implemented soon.

In our view, presumed mobility is legally, economically, and administratively more feasible than the alternative of prohibiting coastal development. First, prohibitions of development are often ruled as contrary to the "due process" clause of the Constitution. By contrast, requirements to yield property to the state as shores erode have been part of the riparian laws of many states since colonial times; bulkheading restrictions are commonplace; and the courts have found that a coastal management action is not a "taking" if the impact is a negligible fraction of a property's value. (Note: the present value of losing a $100,000 property fifty years hence is less than $1,000, and one-hundred years hence, less than $10.)

The latter aspect also explains why the presumed mobility policy would be more economically feasible than prohibiting development. To purchase a few million acres of land that might be wetlands with a one or two meter rise today, would cost tens of billions of dollars; and it would be a poor investment if the greenhouse effect were curtailed and the sea did not rise as projected. By contrast, some ways of implementing the presumed mobility approach (e.g., bulkhead regulations) would require little if any public expenditures; even eminent domain purchases of the option to take over property as sea level rises would be at most a few percent of the property values. If sea level does not rise as projected, the investment to protect coastal wetlands would be lost, just as farmers hedging against decreases in crop prices lose their investments in commodity options if prices rise and homeowners lose the value of their fire insurance premiums if their houses do not burn. In either event, economic theory generally finds hedging and insurance to be rational investments.

Finally, the presumed mobility approach is more administratively feasible because governmental decisions are confined to setting an environmental constraint--the long-term protection of wetlands--rather than dictating the methods by which private landholders meet the constraint. Unlike prohibitions of development, one must concede the eventuality of sea level rise before opposing a policy of presumed mobility. Moreover, preventing development of coastal lowlands would require drawing a line on a map beyond which the land would not be developed; drawing the line would require a decision regarding what level of sea level rise to anticipate, which would in turn require policy makers to (1) rely on a projection of sea level rise, and (2) pick a year after which the policy would be ineffective. By contrast, presumed mobility allows (in fact, requires) real estate markets to incorporate the assessments of buyers and sellers regarding how much the sea will rise and the present value of losing land at some future date.

So far, our argument in favor of the presumed mobility approach has been nothing more than a logical hypothesis; it has not been possible to estimate the practical significance of our arguments. The State of Maine has extended its coastal protection policies to include long-term mechanisms to ensure the survival of coastal wetlands as sea level rises; but no one else has yet followed suit. Whether this is because coastal policy makers disagree with our hypothesis or they simply feel that the matter is not sufficiently urgent to require action, we believe that they need an assessment that estimates costs, remaining wetland acreage, and percentage of the coast with a band of at least (for example) 100 meters of wetlands, for various policy options and implementation dates.

We are now close to having sufficient geomorphic and engineering data to conduct such an assessment for a sample of 46 sites throughout the nation; but we still need projections of economic development for the areas. Moreover, economic models have to be developed to project both annual economic losses and current impacts on property values for a given time profile of the probability distribution of future sea level rise. These models will have to address strategies for physical and economic depreciation of properties. Property owners certain to lose their property in five to ten years would allow their properties to physically depreciate by avoiding major repairs. Owner-occupied property likely to be inundated 20-30 years later could be sold to rental investors who viewed the future more than twenty years hence as irrelevant. People concerned about permanent family ownership of property would tend to buy property in areas that were likely to be protected, but fairly modest price differences would induce investors to purchase property even if inundation were only 20-30 years away. Nevertheless, these strategies would not avoid all of the losses experienced by long-term property owners, who might have attachments to a community or might have invested in additions that command little premium on the rental market.

Incorporating these issues appears manageable. We have an opportunity to evaluate a policy whose benefits may be an order of magnitude greater than the costs. We hope that such an assessment can be undertaken soon.

Because the situation is very different than for the rest of the nation's coast, this report has not focused on Louisiana. Unlike wetland loss elsewhere, the implications of sea level rise for this coastal state appears almost certain to require federal action, because the federal government manages the flow of the Mississippi River. A recent EPA/Louisiana Geological Survey report outlined the analysis necessary to evaluate options to protect Louisiana's coastal wetlands. With 40% of the nation's coastal wetlands at risk and the federal government preventing freshwater and sediment from reaching the marshes and swamps, wetland loss in Louisiana cannot realistically be viewed as the parochial concern of a single state.

REFERENCES

Alexander, C.E., M.A. Broutman, and D.W. Field. 1986. An Inventory of Coastal Wetlands of the USA. Rockville, MD: National Oceanic and Atmospheric Administration.

Barth, M.C. and J.G. Titus. 1984. Greenhouse Effect and Sea Level Rise: A Challenge for This Generation. New York: Van Nostrand Reinhold.

Bruun, P. 1962. "Sea Level Rise as a Cause of Shore Erosion. Journal of the (ASCE) Waterways and Harbors Division 88 (WW1):117-130.

Dean, R.G. et al. 1987. Responding to Changes in Sea Level. Washington, D.C.: National Academy Press.

Devoy. R.J. 1987 Sea Surface Studies. New York: Croom Helm.

Everts, C. 1985. In Potential Impacts of Sea Level Rise on the Beach at Ocean City, Maryland. Washington, D.C.: Environmental Protection Agency.

Hallermeier, R.J. 1981. "A Profile Zonation for Seasonal Sand Beaches from Wave Climate." Coastal Engineering 4:253-277

Hansen et al. 1986. In Titus, J.G. (ed). Effects of Changes in Stratospheric Ozone and Global Climate. Washington D.C.: Environmental Protection Agency and United Nations Environmental Program.

Hull, C.H.J., L. Thatcher, and R. Tortoriello. 1986. "Impact on Delaware River Salinity." In: Hull and Titus, op. cit.

Hull, C.H.J. and J.G. Titus. 1986. Greenhouse Effect, Sea Level RIse, and Salinity in the Delaware Estuary. Washington, D.C.: Environmental Protection Agency.

Kana, T.W., B. Baca, and M.L. Williams, 1984. Potential Impact of Sea Level Rise on Wetlands Around Charleston, South Carolina Washington, D.C.: Environmental Protection Agency.

Kana, T.W., B.J. Baca, and M.L. Williams. 1988. "Charleston Case Study." In: Titus (ed), 1988.

Kriebel and Dean 1985. Potential Impacts of Sea Level Rise on the Beach at Ocean City, Maryland. Washington, D.C.: Environmental Protection Agency.

Louisiana Wetland Protection Panel. 1984. Saving Louisiana's Coastal Wetlands: The Need for a Long-Term Plan of Action

Sorensen, R.M., R.N. Weisman, and G.P. Lennon. 1984. "Control of Erosion, Inundation, and Salinity Intrusion Caused By Sea Level Rise." In: Barth and Titus. op. cit.

Titus, J.G. 1986. "Greenhouse Effect, Sea Level Rise, and Coastal Wetlands.' Coastal Zone Management Journal. 14:3.

Titus, J.G. 1985. "Sea Level Rise and the Maryland Coast." In Potential Impacts of Sea Level Rise on the Beach at Ocean City, Maryland. Washington, D.C.: Environmental Protection Agency.

Titus, J.G. (ed) 1988. Greenhouse Effect, Sea Level Rise, and Coastal Wetlands. Washington, D.C.: Environmental Protection Agency.

Titus

Titus, J.G., T. R. Henderson, and J.M. Teal. 1984. "Sea Level Rise and Wetlands Loss in the United States." National Wetlands Newsletter Environmental Law Institute: Washington, D.C. 6:5.

Titus, J.G., T. R. Henderson, and J.M. Teal. 1984. "Sea Level Rise and Wetlands Loss in the United States." National Wetlands Newsletter Environmental Law Institute: Washington, D.C. 6:5.

Titus, J.G., C. Kuo, M.J. Gibbs, T. Laroe, K. Webb, and J. Waddel, 1987. Greenhouse Effect, Sea Level Rise, and Coastal Drainage Systems. ASCE Journal of Water Resources Management.

APPENDIX 1.

Proof that the Ratio of Costs in the Year 2100 for different sea level rise scenarios is a conservative approximation of the ratio of total costs, assuming the Weggel formula.

First, we simplify notation by letting $x(t)$ and $y(t)$ represent the costs of the 1 and 2 meter scenarios, and A represents the ratio $x(2100)/y(2100)$. It is commonly known that if $x(t) \geq A * y(t)$ for t over a given range (in our case 1990 to 2100), then,

$$\text{(A1)}\quad \int_{t=1986}^{2100} x(t)\,dt \Big/ \int_{t=1986}^{2100} y(t)\,dt \geq A$$

Therefore, $x(2100)/y(2100)$ is a conservative estimate provided that $x(t)/y(t)$ is in fact greater than $x(2100)/y(2100)$ for $t<2100$, which we now show.

First, we note that sea level rise accelerates over time, which means that,

$$\text{(A2)}\quad \mathrm{SLR\_1m}(t)/\mathrm{SLR\_2m}(t) > \mathrm{SLR\_1m}(2100)/\mathrm{SLR\_2m}(2100),$$

throughout the period 1986 to 2100. We define the latter ratio (for 2100) as **B**, which is less than one. Therefore, recalling that,

$$\text{(A3)}\quad x(t)/y(t) = \frac{((5+\mathrm{SLR\_1m}(t))/5)^{1.5}-1}{((5+\mathrm{SLR\_2m}(t))/5)^{1.5}-1},$$

We substitute $B*\mathrm{SLR\_2m}(t)<\mathrm{SLR\_1m}(t)$, and get,

$$\text{(A4)}\quad x(t)/y(t) > \frac{((5+B*\mathrm{SLR\_2m}(t))/5)^{1.5} - 1}{((5+\mathrm{SLR\_2m}(t))/5)^{1.5} - 1}.$$

For clarity, we redefine $\mathrm{SLR\_2m}(t)$ as $z(t)$,

$$\text{(A5)}\quad x(t)/y(t) > \frac{((5+B*z(t))/5)^{1.5} - 1}{((5+z(t))/5)^{1.5} - 1}.$$

Since $z(t)$ is monotonically increasing, and B is positive but less than 1, it is clear that $x(t)/y(t)$ is monotonically decreasing. Therefore, $x(t)/y(t)$ is in fact greater than $x(2100)/y(2100)$ for all years before 2100, and the assertion is proven.